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A Story of Plate Tectonics and Earth Tides

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On the History of the Continents

A Story of Plate Tectonics and Earth Tides

by

Flemming Bo Pedersen

2011

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A Story of Plate Tectonics and Earth Tides

LICengineering A/S

Ehlersvej 24

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PREFACE

The present monograph is published to honour Dr. Tech. Flemming Bo Pedersen, Professor Emeritus in Hydrodynamics at the Technical University of Denmark, on his seventy year's birthday and in gratitude for his continuous support to LICengineering A/S.

Professor Emeritus, Dr. Tech. Flemming Bo Pedersen

The monograph collects Professor Emeritus, Dr. Tech. Flemming Bo Pedersen research and findings on plate tectonics during the last fifteen years.

A new theory for plate tectonics and the evolution of Earth is introduced in the monograph. The governing force for the movement of the continents is concluded to be the long period earth tides.

LICengineering A/S, Marts 2011

Niels-Erik Ottesen Hansen

ACKNOWLEDGEMENTS

In writing this monograph "On the History of the Continents - A Story of Plate Tectonics and Earth Tides" I have been supported and helped by many colleagues' and friends. Especially I want to thank:

- Director and founder of LICengineering A/S, Dr. Niels Erik Ottesen Hansen for publishing my spare time research on continental drift in his Monograph Series.
- Senior Engineer in LICengineering A/S, Dr. Flemming Jakobsen for enthusiastic help with improving the final manuscript and making it ready for print.
- Senior Technical Designer at LICengineering A/S, Ken Jensen for preparing the drawings for print.
- Professor, Dr. Katherine Richardson for support during the long process of writing a manuscript on the subject.

The responsibility for any mistakes – professional and/or linguistic – in this final version of the manuscript is in full undertaken by me.

Lyngby, 27th February 2011

Flemming Bo Pedersen

TABLE OF CONTENT

1. INTRODUCTION

Our planet is shaped by plate tectonic processes, since nearly all geological processes, past and present, are influenced by plate tectonic. Hence a reconstruction of the history of the continents should be possible provided our understanding of plate tectonics is sufficiently adequate.

The current literature on plate tectonics offers two different viewpoints of what are the major driving mechanisms, namely convection in the interior (see *Figure 1-1*) and/or slab pull from the dipping ocean plates and hydrostatic ridge push.

As will be demonstrated in Chapter 5, with these proposed mechanisms as the only active drivers of plate tectonics, the Earth would have been a sterile planet with an unbroken outer shell, i.e. with no continents, no ocean ridges, no subduction zones, etcetera.

A critical analysis of the driving mechanism in plate tectonics is therefore carried out in Chapter 3, which yields the following key results:

- Convection in the Earth interior is unable to split and drive ocean plates and/or continents;

- Slab pull from ocean plates sinking into the interior of the Earth at ocean trenches is unable to split the plate but an important driver of plates supplied with a slab;

- Hydrostatic ridge push is unable to split plates and just a minor driver of plates.

It is therefore of decisive importance to find the hitherto unrecognized universal driver of plate tectonics, which is able to shape the Earth with continents, oceans and divergent and convergent boundaries. This is the subject of Chapter 4. It turns out to be the so-called long period earth tides (see *Figure 1-2*), caused by the orbital motion of the Sun (period a year) and the Moon (period a month).

This is apparently a paradox, since the stresses involved in earth tides are insignificant compared with for instance the stresses released in an earthquake. The key to understand the role of earth tides is in brief:

- Because the forces created by the long period earth tides are independent on the longitude the east-west deformations concentrate on the tension weak north-south divergent boundaries, which open up during the extension half cycle period.

- The associated reduced pressure below the mid-ocean ridge creates a partial melting of the mantle.

- The melted rock ascends by buoyancy to fill the gaps in the magma chamber.

- During the succeeding half cycle period of compression part of the magma solidifies to form the new crust at the ridge.

Hence, this is in brief the hitherto misunderstood and therefore neglected universal and important driver of plate tectonics. By observations and predictions it is proved that it is a theory with a broad observational data base in its support.

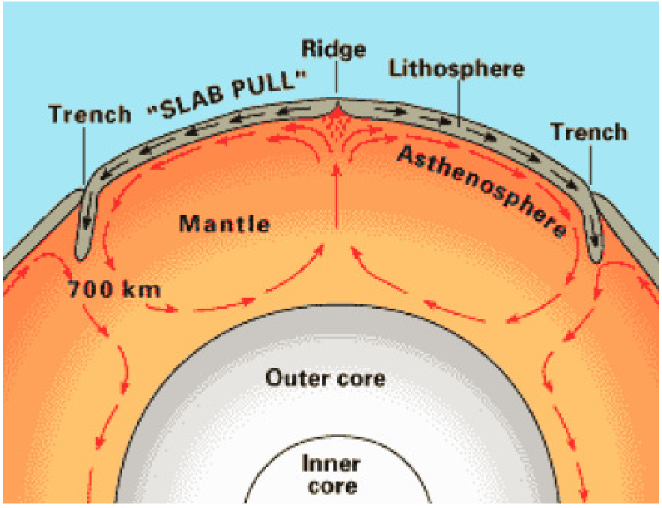


Figure 1-1 Convection in the Earth interior. Adapted from Kious and Tilling (1996).

Convection as a driver of plate tectonics is replaced by long period earth tides as a prime driver of plate tectonics.

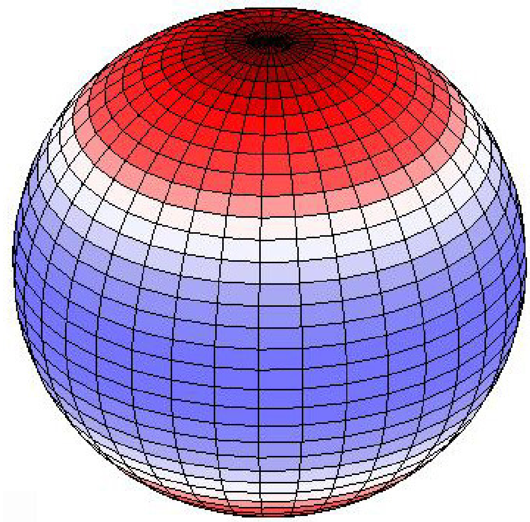


Figure 1-2 Sketch illustrating the deformations of the Earth due to one of the constituents for the long period earth tides during the first half cycle. Deformations are rotationally symmetric, symmetric about the equatorial plane and varying with the latitude (see Figure 4-4): The white ring at latitude +/- 35.26° marks the rings of no deformations; the blue equatorial belt experience an elevation of the Earth (and hence a stretching of the surface area) with maximum value at Equator ; the two red skullcaps at the poles do at the same time experience a lowering of the surface (and hence a compression of the surface area) with a maximum lowering at the poles. During the succeeding half cycle the deformations outside latitude +/- 35.26° are just opposite. Adapted from www.en.wikepedia.org/wiki/Earth_tides.

With this knowledge at hand a chronological reconstruction of the history of the continents can be carried through, which is done in Chapter 5. The reconstruction is divided in Epoch I to VI as follows:

Epoch I: Rotating self-gravitating inhomogeneous masses. Sorting of the aggregated gasses and other cosmic material, which became the Earth, in "pycnospheroids". The Geoide.

Epoch II: Cooling and formation of crust floes, growing thicker and greater with time. Formation of median and latitudinal fracture zones by earth tides.

Epoch III: The origin of ocean plates and continents, respectively. Creation of the two symmetric subsea Polar Supercontinents, Gondwanaland and Laurasia separated by the Super Ocean, the Tethys Sea (see *Figure 1-4*). The locked Polar skullcaps grow thicker (exponentially) with time due to the long period earth tides mechanism (the growth rate is calculated and confirmed by observations, which allows solving the problem of the next epoch).

Epoch IV: First appearance of land at about 600 Ma, a consequence of isostatic equilibrium. Dramatic increase in oxygen content in the atmosphere. Fossils of the first fish with legs from this period.

Epoch V: Fragmentation of the Supercontinents into present day's continents. The exponentially growing unbalance in the rotating Earth caused by the export of huge masses from the Equatorial zone (below 35.26° latitude) to the two Polar zones (above 35.26° latitude) eventually results in a Equator-wards gravitational force strong enough to initiate the movement of the fragmented continents towards Equator in order to partly restore the rotational balance of the Earth. This happen about 160 Ma. The continental drift has been governed by ridge push caused by long period earth tides combined with slab pull.

Epoch VI: The continental drift towards present days positions of continents, oceans and convergent and divergent boundaries. The result is an unmistakable picture of present-day Earth's continents, oceans, divergent and convergent boundaries. This analysis gives some extra bonus, such as an explanation for the bend of the Hawaiian – Emperor Seamount Chain, which has the same cause as the westwards displacement of the Atlantic Mid-Ocean Ridge across Equator and of North America relative to South America and of India relative to Australia.

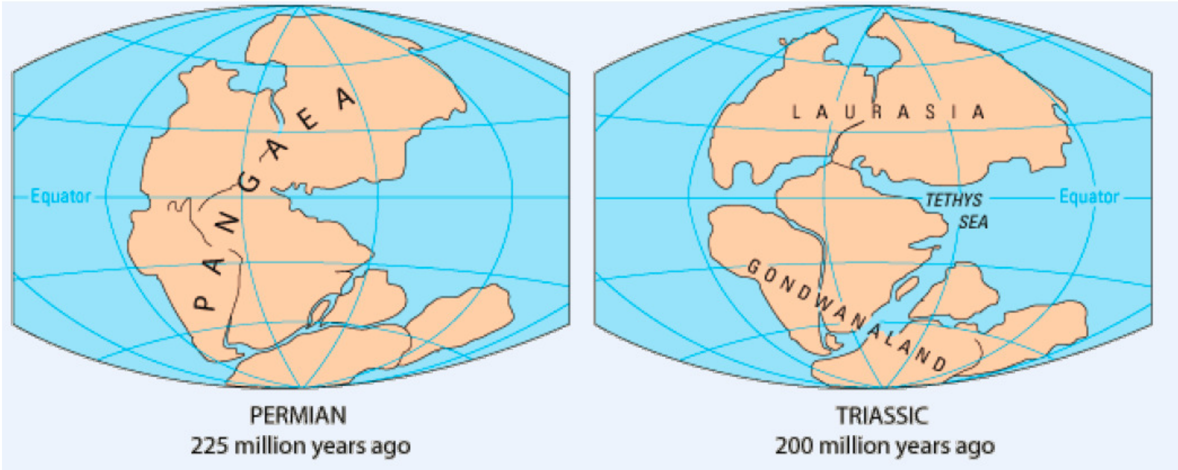


Figure 1-3 The hypothetical supercontinent Pangaea and its sub-continents Laurasia and Gondwanaland. Adapted from Kious and Tilling (1996).

Pangaea is replaced by two polar supercontinents of equal sizes.

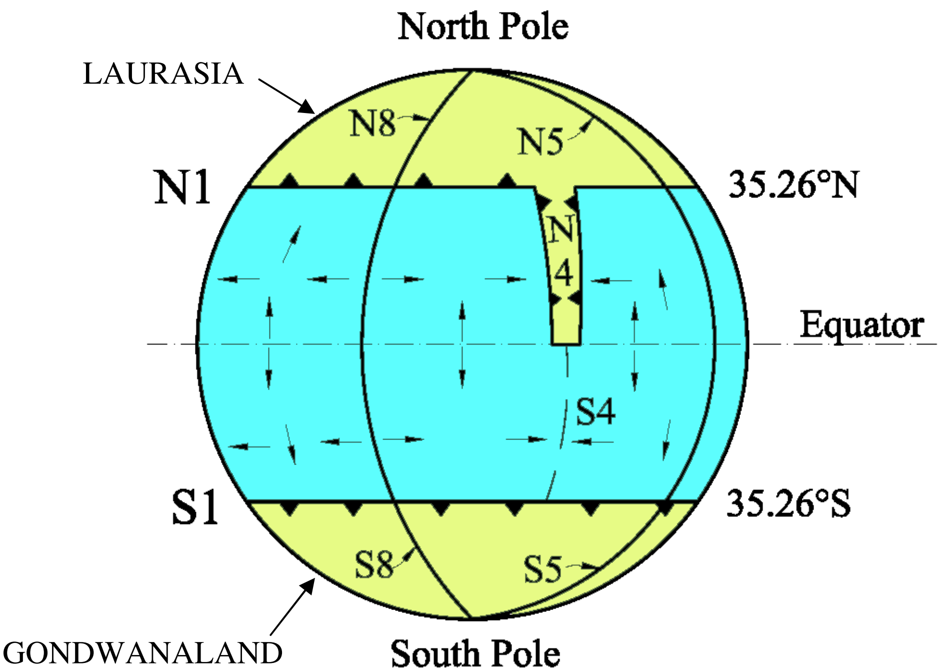


Figure 1-4 A diagram of the two super continents Laurasia and Gondwanaland separated by the Tethys Sea. A product of earth tides.

2. BACKGROUND ON PLATE TECTONICS

Plate tectonics is the theory that explains the behaviour of the uppermost layers of the Earth, which is divided into a number of thin, quasi-rigid plates which are in relative motion with respect to one another. Those parts of the outer shell that participate in these movements are referred to as the lithosphere, a relatively cool and rigid rock with an average thickness of about 100 km beneath the ocean basins; beneath the continents the average thickness is about twice this value. The rocks beneath the lithosphere comprise the asthenosphere, relatively hot and deformable solid rocks which allow the lithosphere to slide over it with relatively little resistance.

The complementarities of the shapes of coastlines on opposite sides of the oceans have during time fascinated many scientist, among them the German meteorologist Alfred Wegener, who published his theory of continental drift in 1915 (see the translation of Wegener's book from 1966), supplemented with paleontological, zoological and botanical evidences. Although Wegener's theory was not generally accepted at that time by the geologist he is now regarded as the godfather of plate tectonics. The real breakthrough came in the wake of Second World War, during which several American scientist were drafted to the marine. The many accurate observations and registrations of the conditions prevailing on the ocean bottom finally led the American geologist Harry H. Hess in 1962 to propose that the continental drift was governed by the process of sea-floor spreading at the mid-ocean ridges. The global system of mid-ocean ridges is shown in *Figure 2-1*.

The ocean lithosphere is typically split up into narrow strips separated by fracture zones; often deep valleys in the seafloor running east-west or north-south in extension of the ridge-ridge transform faults, see *Figure 2-2*.

The rigidity of the continental lithosphere allows the plates to transmit elastic stresses during geologic time scales, forming mountains in response to a horizontal pressure and bending under vertical loads. There are three types of plate boundaries with the following characteristics, see *Figure 2-3*:

1. Divergent boundaries or accreting boundaries. These boundaries are primarily the mid-ocean ridge system, where fluidized magma flows upwards from the mantle to fill the gap created by the plates moving away from each other. Secondary, continental rifts are divergent boundaries giving birth to a split up of a continent. The resistance to tension is markedly reduced at the mid-ocean ridges, partly because the lithosphere is very thin here and partly because the underlying magma chamber is more ductile. The mid-ocean ridges typically have an orthogonal fault-ridge geometry, forming a zigzag ridge system. The faults and the ridges do apparently prefer to run nearly north–south and/or east-west. According to Turcotte and Shubert (2007) is the basic physics generating the orthogonal pattern not understood (an explanation based on the earth tides theory is offered in Chapter 4). Ocean ridges are sites with a large fraction of the Earth's volcanism.

2. Convergent boundaries. As the oceanic lithosphere moves away from the ridge, it cools, thickens and becomes denser by thermal contraction and hence it gradually sinks. Eventually it becomes gravitationally unstable with respect to the hot mantle rocks below and it starts to sink into the interior of the Earth often at an ocean trench. The horizontal component of the gravity force on the subducting ocean plate is the so called slab pull, an important force in plate tectonics. Great stresses are accumulated between

the ocean plate and the overlying continental plate. Periodically these stresses are released creating major earthquakes and tsunamis.

3. Transform faults. Here the plates move laterally relative to each other. Great stresses are accumulated along transform faults with time and periodically released creating earthquakes. The extensions of the ocean ridge-ridge faults, the numerous ocean fracture zones behave like transform faults where moderate shear stresses are build up and periodically released (as will be discussed in Chapter 4).

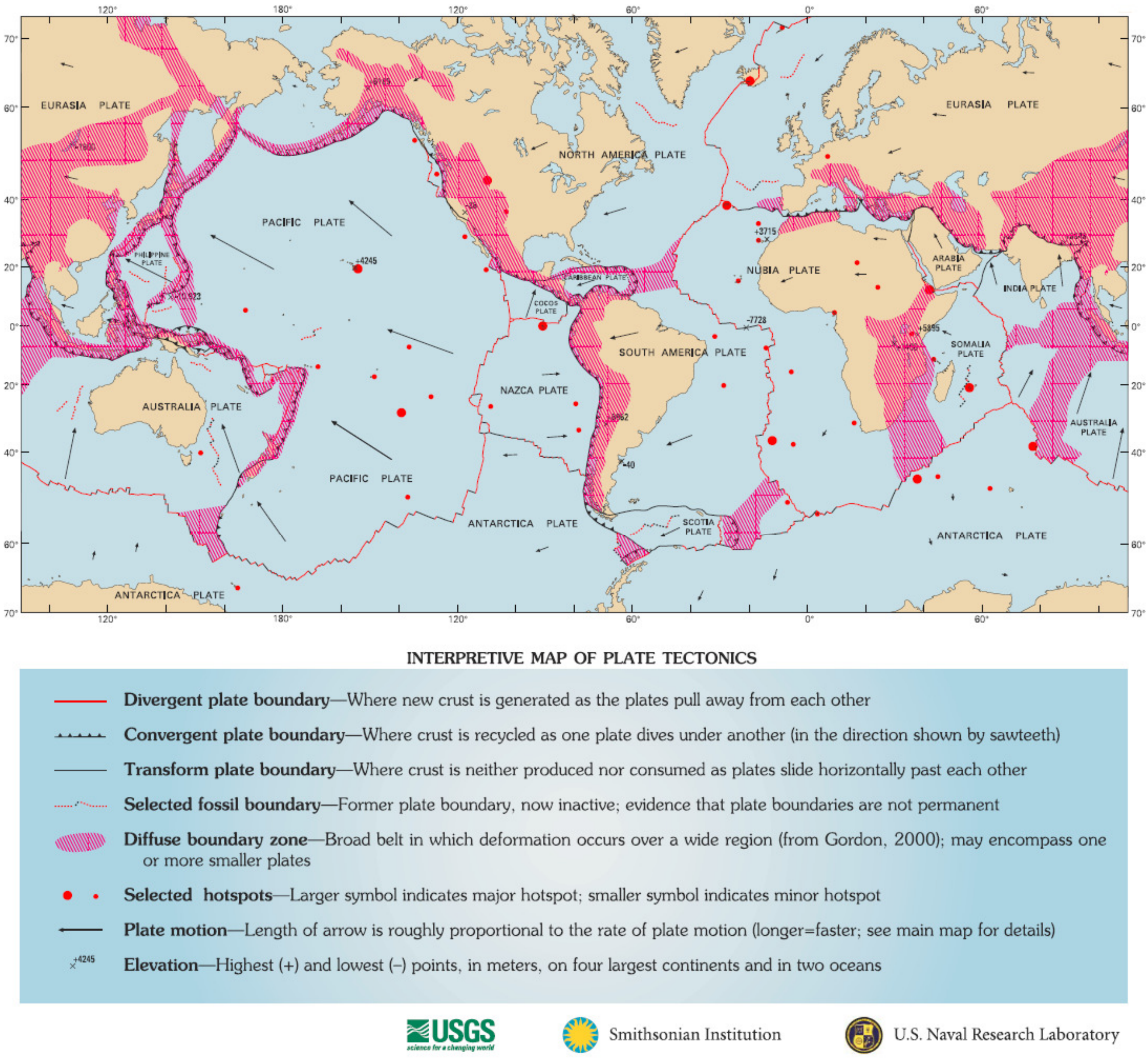


Figure 2-1 Map showing the global system of mid-ocean ridges and the types of plate boundaries. Adapted from MAP (1994).

The horizontal sea-floor spreading at the ocean ridges is an absolute necessity for the creation of new oceanic lithosphere. The cause of plate divergence is therefore the key issue in plate tectonics. The current literature on plate tectonics offers two different viewpoints of what are the major driving mechanisms in sea-floor spreading, namely convection in the interior and/or slab pull from the dipping ocean plates and hydrostatic ridge push caused by the pressure difference (buoyancy forces) between the high elevated thin lithosphere at the ocean ridge and the low elevated, thicker ocean lithosphere far away from the ridge.

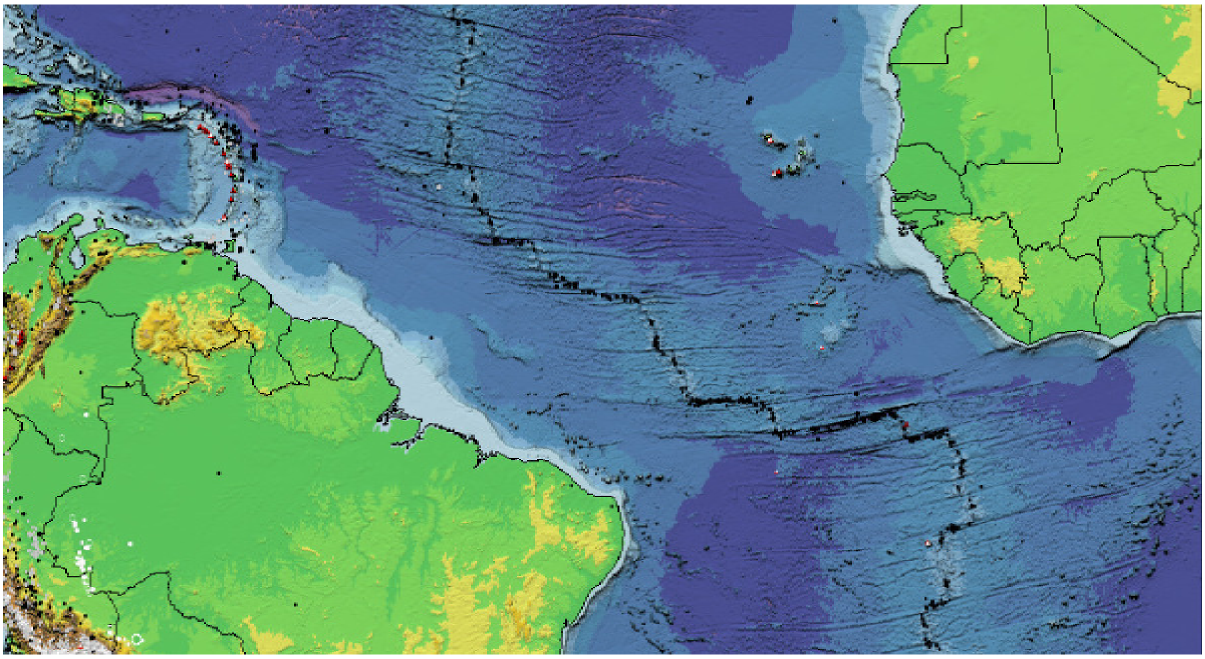


Figure 2-2 Typical east-west running fracture zones in extensions of the ridge-ridge transform faults splitting the ocean lithosphere up in narrow strips. Here an example from the Atlantic Ocean ridge near Equator. Adapted from MAP (1994).

The first viewpoint is that the Earth releases its internal heat by convection which raises the hot asthenospheric mantle towards the surface, where it spreads laterally, transporting oceans and continents as on a slow conveyor belt. There are proven evidence for the existence of hot plumes in the asthenosphere (for instance hot spots) and for movements of the mantle (see for instance Vandecar et al., 1995), but this is not tantamount to the convection being a major driving force. As will be demonstrated below it is not.

Another viewpoint is that the plates sliding over the partially molten mantle is pulled at one end by the slab dipping into the mantle at subduction zones, pushed at the other by new magma welling up at mid-ocean ridges (ridge push). Notice that if the lithosphere is in isostatic equilibrium, then the net hydrostatic ridge push only amounts to 1/10 of the slab pull (Forsyth and Uyeda, 1975; Turcotte and Schubert, 2007 and Fowler, 2009). Slab pull is not a universal driver of tectonic plates, simply because important plates do not have a slab.

Instead of being left with an unanswered question of what drives the plates, the hypothesis of the long period earth tides as being the candidate is investigated in the present monograph.

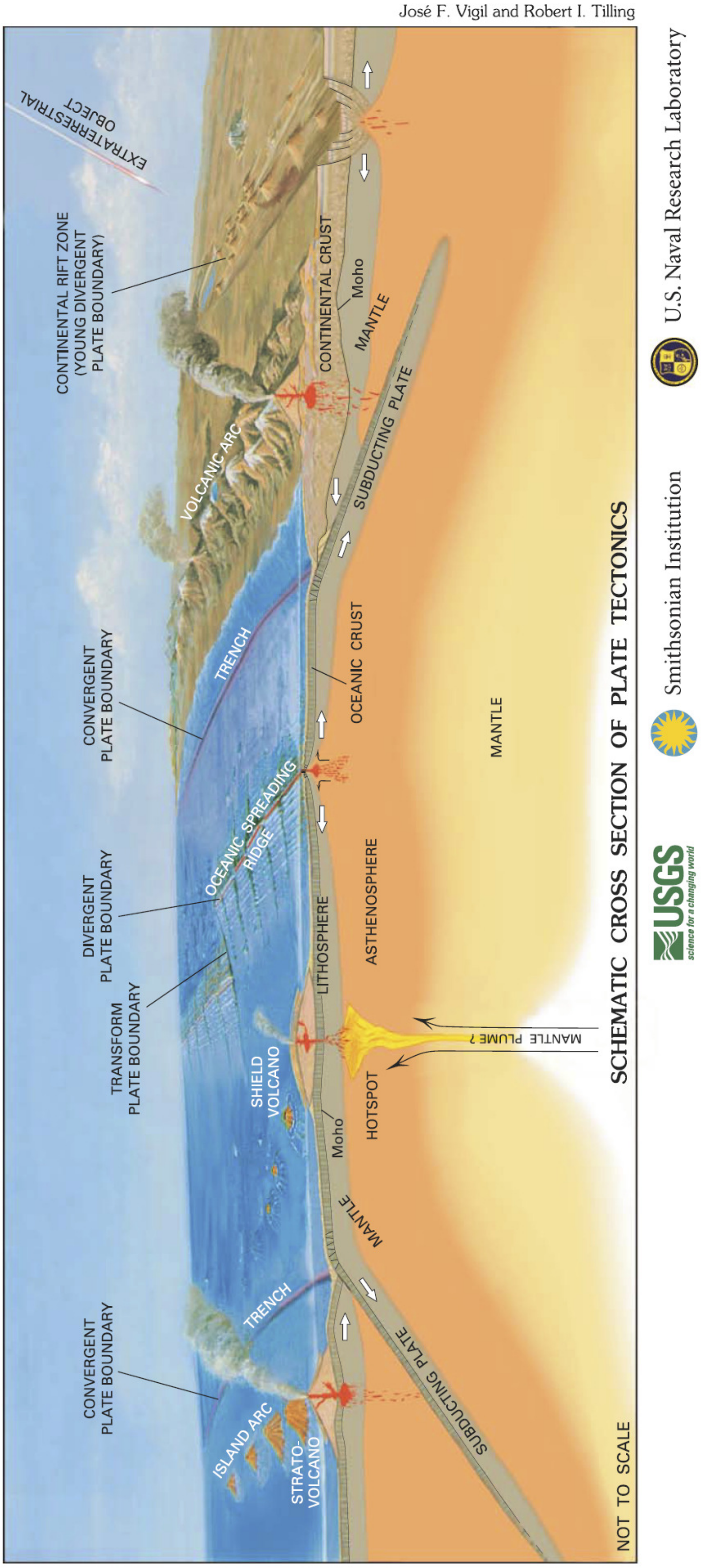


Figure 2-3 Sketch of the cross-section through outer part of the Earth illustrating the plate tectonics processes. Adapted from MAP (1994).

3. UNDERLYING PHYSICAL PROCESSES IN PLATE TECTONICS

3.1 Introduction

The basic fluid dynamics of convection flows are briefly summarised. With this knowledge at hand the existence of huge convection cells below the tectonic plates is given a close examination. After having performed a broad spectrum of consequence analysis of the physics of convection cells in the Earth's interior, it can beyond any doubt be concluded that convection cells do not transport the plates.

Similarly, it can beyond any doubt be concluded that slab pull is not the universal plate driving mechanism, simply because many important plates do not have sub ducting plates.

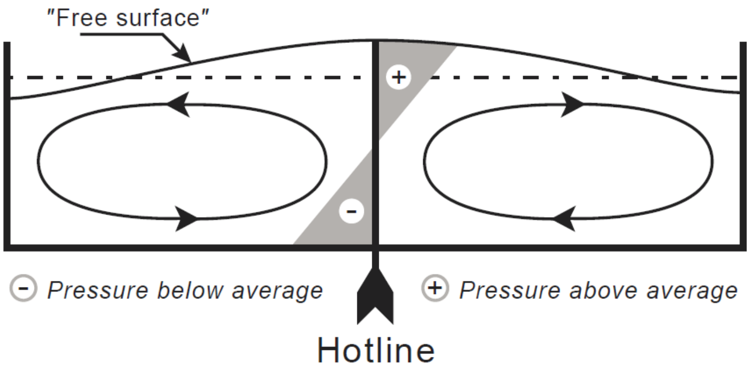
3.2 Convection Hypothesis

The transport induced by hydrostatic instability, such as the flow over a heated plate, is named convection. The heat flux leads to density differences, which combined with gravity produces the motion. The difference in weight per unit volume $-g \cdot \rho$ is called the buoyancy, where the minus sign has been used because a particle is said to be more buoyant when it has less weight. Hence the so-called convection cells in plate tectonics have the same physical background as buoyancy driven circulation in hydrodynamics and the thermohaline circulation in oceanography, see e.g. Bo Pedersen (1986).

To judge the physical reality in the hypothesis of convection cells acting as driving mechanism in plate tectonics, a brief summary of some relevant findings on buoyancy driven circulation is pertinent. As a frame of reference we first consider a two dimensional long wall insulated box heated from below in a limited region in the middle (in the following this heat source is called a hotline), see the illustration *Figure 3-1a*. The hydrostatic instability causes the heated fluid to rise above the hotline as a plume. The reduced weight of the fluid column above the hotline causes the local pressure to drop, which creates the lateral pressure gradient needed for transporting new fluid to the hotline plume to keep up the flow. When the rising plume reaches the surface an elevation of the surface takes place to adjust to the buoyancy and hence the hereby established pressure gradient causes the fluid to spread laterally to both sides. In case a heat loss from the surface takes place the temperature and hence the buoyancy decreases in downstream direction, lowering the fluid level and therefore maintaining the flow.

Eventually the heat loss, the mass conservation and the mixing yield the fully developed steady state circulation, where the heat input is balanced by the heat loss. The heat loss from the surface may remove the buoyancy before the flow reaches the end wall. In that case the surface heat loss put a limit on the extension of the cell, which becomes less than the length of the box. Otherwise, the circulation goes to the end wall. The lateral pressure gradients caused by the variation in the buoyancy distribution drives this two-cell circulation. For the sake of illustrating the driving forces the fluid level has been drawn in a distorted scale. In nature this deformation of the surface can be measured as gravitational anomalies. The super elevation above the lowest fluid level yields the lateral pressure gradients in the top of the fluid, which drives the surface layer (downhill) away from the heat source. The vertical buoyancy distribution decreases the lateral pressure gradient with depth as illustrated by the hatched triangles in *Figure 3-1a*. Halfway down the horizontal pressure gradient change sign and the flow direction changes accordingly. One notices that if a light plate is placed on the surface of one of the two cells, i.e. where the flow is one-way, the plate will be transported in the same direction as the surface of the fluid due to gravity and friction. On the other hand, if the same plate covers an equal part of the two opposite directed circulating cells, the plate will not be moved because the gravity component is zero as is the sum of friction from the current.

a)



b)

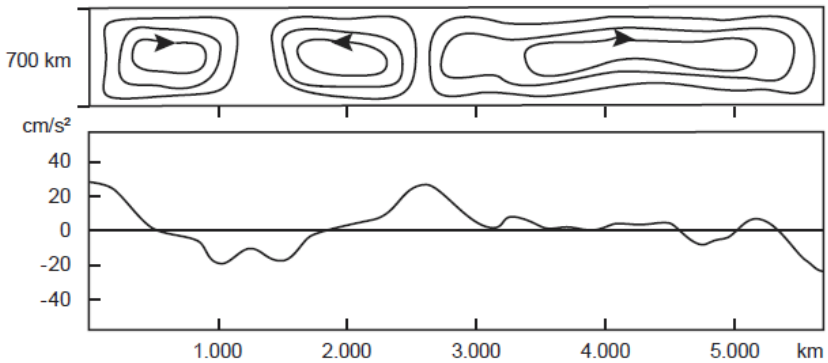


Figure 3-1 ***a)*** *Steady buoyancy driven two-cell circulation in a confined, insulated two-dimensional box heated from below along a central concentrated line (hotline) and cooled from above. The hatched triangles show the buoyancy generated hydrostatic pressure. The "free surface" reflexes the expansion of the fluid column due to the heating (i.e. a measure of the gravity anomaly).*
b) *Numerical simulation of convection in a two-dimensional 700 km deep box heated uniformly from below and cooled from above. Upper panel is a snapshot of the complicated, time varying buoyancy driven circulation. Two rising plume eruptions of heated material are seen near the centre and to the left. Two sinking regions with colder material are located to the right and at the left quarter. Lower panel shows the calculated variation in the local acceleration of gravity (the gravitational anomaly) caused by the variation in buoyancy of the material (confer with the "free surface" variation in Figure a). The sketches have been adopted from McKenzie (1983), who performed the numerical simulation.*

In the second frame of reference the same box with fluid is now heated uniformly from below. Laboratory experiments in water shows that the hydrostatic instabilities at the bottom creates a boundary layer where the unstable fluid is collected in minor volumes which suddenly rises as an eruption, creating a stochastic pattern of eddies in the water column above. In the ductile magma inside the Earth the response is most likely the same, but no doubt with different eddy length scales and definitely with much greater eddy time scales, because of the very different material constants. Hence, to learn from the experiments with a uniform heating from below, we adopt the results obtained by McKenzie (1983) from a numerical model with Earth relevant physical parameters, see *Figure 3-1b*. This method is in many ways complementary to the more physically oriented approach used above. The results from the numerical model were compared with field observations of gravitational anomalies reflecting the pattern of rising and sinking regions. The two patterns agree in all essentials, confirming that below the Pacific Plate is the extent of a pair of convection cells with opposite directed currents about three to four times the depth of convection. As the depth was 700 km, it leaves space for at least 5 pairs of convection cells in the east-west direction of the Pacific Plate or in the order of magnitude of 25 pairs of cells under the whole Pacific Plate.

With this basic fluid dynamic knowledge about convective flow in mind, the existence of huge convection cells below the ocean plates can be given a close examination.

- A prerequisite for the existence of only one huge convection cell underlying a whole tectonic plate is that the heat input is concentrated in certain narrow regions, here named hotlines, located just below the spreading mid ocean ridges to fix the rising starting point of the cell.

- Suppose that a plate is located between two nearly parallel hotlines, such as the African Plate between the Mid-Atlantic Ridge and the Central-Indian Ridge-Arabian-Indian Ridge (MAP, 1994). Above both hotlines the heated magma rises to the surface and spreads laterally on either side. Hence under the present plate the two currents initiated at the two hotlines are flowing against each other until they join and sink, for instance at the middle of the plate, if the two heat sources have the same strength. Therefore, two opposite directed cells are created, i.e. no resulting one-way directed convection surface flow could be established under such a plate.

- The scenario is even more extreme for the huge Antarctic Plate, which is a skullcap almost bounded by ocean ridges all around its circumference. Here the geometry forbids the formation of any major convection cell due to concentrated heating along the circumference. Hence, this plate should not be moving, in obvious contradiction to observations.

- Below it is demonstrated how the convection theory fails to explain the observed consequences for the seafloor spreading of the Mid-Atlantic Ridge caused by the slowdown of the African Plate some 30 million years ago.

- One absolute prerequisite for creating the plate driving convection cell is that all the mid ocean ridges are located just above hotlines. As the imagined hotlines like the hotspots must have fixed positions at the outer core of the Earth, this implies that the positions of the ridges should be fixed too. This consequence is in obvious contradiction with observations, for example the continuous widening of the African Plate, which separates the two nearly parallel ocean ridges.

Based on his numerical model McKenzie (1983) reached many conclusions in accordance with the statements above. The numerical model calculation showed a complicated and time varying flow pattern (*Figure 3-1b*), indicating the same behaviour as explained above for a water volume heated uniformly from below, namely a pattern of chaotic eddies in space and time, but of course in really slow motion. The eddy sizes (the cells) of two counter current cells were three to four times the depth. Based on isotope measurements on Hawaiian lava (located above a hotspot), he showed that the material from the volcano has not been well mixed with the rest of the upper mantle. This is in agreement with the measured gravitational anomalies plotted by McKenzie (1983), which shows that the hotspot plume below Hawaii is surrounded by a number of convection cells of approximately the same size as in the numerical model. Finally, McKenzie (1983) concluded that the upwards flow do not coincides with the position of a mid-ocean ridge, again in accordance with the arguments above.

The buoyancy driven convection cells exist, but do not transport oceans plates and continents. As a consequence of mass conservation, a compensating flow from the convergent zones towards the divergent zones must be present, i.e. a flow against the movement direction of the overlaying plate. Moreover, the shear stresses in the asthenosphere imposed by the plate movement may generate a weak-circulating current in the underlying magma, where the upper part of the flow is in the plate movement direction.

3.3 Slab Pull Hypothesis

In the thorough analysis of plate driving forces by Forsyth and Uyeda (1975), many other convincing arguments are given, which lead to the same conclusion, namely that the asthenosphere is passive and plays only the role of providing the return flow (compensation flow caused by plate subduction). In addition, they found that slab pull is the most powerful plate driving force. However, it can be concluded that slab pull cannot be a universal plate driving mechanism, simply because many important plates do not have subducting plates. Finally they found that ridge push was an active plate driver but the moderate hydrostatic buoyancy pressure caused by the uplift and injection of hot mantle material was only 1/10 of the slab pull. Therefore, in their model ridge push is not able to actively split up the plates, only helping to push the plates apart after they have been separated. In summary:

- There are several important plates without a sub ducting part. Nevertheless, these plates are able to move, see for instance the African Plate, the South American Plate, the North American Plate and the Antarctic Plate.

- So, although slab pull is known to be of importance at the Pacific Plate, the Australian Plate and the Nazca Plate, it cannot be the universal driving force of the tectonic plates.

3.4 Conclusion on the Existing Plate Driving Hypothesis

A broad spectrum of consequence analysis of the physics of convection cells in the Earth's interior do beyond any doubt demonstrate that convection cells do not transport the plates.

Similarly, it can beyond any doubt be concluded that slab pull is not the universal plate driving mechanism, simply because many important plates do not have sub ducting plates.

Nevertheless, heat transport from the interior of the Earth is indirectly an important factor in plate tectonics, as it creates the buoyancy which gives rise to slab pull, ridge push and upwards flow of ductile magma at the mid-ocean ridges.

Instead of being left with an unanswered question of what drives the plates, the hypothesis of the long period earth tides as being the candidate is investigated thorough in Chapter 4.

Another more firm approach to recognize the need of an alternative driving mechanism in plate tectonic is presented in Epoch II in the reconstruction process (see Chapter 5). Here it is shown that without an alternative driving mechanism such as the long period earth tides, continents would never have been formed on Earth.

4. LONG PERIOD EARTH TIDES AS DRIVER OF PLATE TECTONICS

4.1 Introduction

The surface layer of the solid Earth responds elastically to the tide-producing forces in such a way that the shape assumed by the solid Earth is always in equilibrium with the forces (Munk and McDonald, 1975). The presence of fractures in the shell of the Earth does not influence the ability to adapt to the equilibrium shape (Xing et al., 2007). Nevertheless, the equilibrium tide outlined below cannot be applied to the solid Earth without correction. According to Munk and McDonald (1975), the direct response of the solid Earth to the tidal potential produces an elevation of $h \cdot \eta$, where h is the so-called Love number, which takes a constant value of about $h = 0.6$. In the following calculations the Love number h is first taken into account in the final numerical calculations.

First the theoretical background for earth tides is briefly outlined. The candidate to create sea-floor spreading is identified as the so called long period earth tides caused by the orbital motions of the Moon and the Sun, respectively.

This is broadly analogous to processes that operate on Jupiter's satellite Europa. The crust of Europa may consist of ice only a few kilometers thick overlaying liquid water, Turcotte and Schubert (2007). If the tide induced surface strain on Europa is working on preexisting cracks, the following scenario is envisaged in a sequence of cyclic tensional and compressional tidal stresses, see Greenberg et. al. (1998), (citation):

"*Double ridges could plausible be built along the cracks with sizes and morphologies consistent with observed structures, according to a model in which underlying liquid water fills the open cracks, partially freezes, and is extruded during the daily closing of the cracks*". (Comment: Daily means here the 3.55 days sidereal period).

The same mechanism of ridge formation is found in studies on Arctic sea ice. Here it is the varying wind, ocean tide, run off etc. which influence the current which combined with the Coriolis forces occasionally opens up the preexisting cracks in the sea ice, allowing the sea water to fills the open crack, which then partially freezes, and then extrudes during the following closing of the cracks when the impact fall again.

Basically, the physics of the present sea-floor spreading at the mid-ocean ridges is envisaged to broadly be the same as the example of new ice formation on Europa. Meanwhile, there are two major differences, which shall be dealt with, namely:

- The difference in the rheological properties of sea water and magma, respectively; and
- The different sizes and numbers of the openings of the cracks.

A step by step description of the physical processes producing the sea-floor spreading by earth tides is given. By observations and predictions presented it is proved that it is a theory with a broad observational data base in its support. For instance: The theory explains the many ocean fracture zones and the zigzag orthogonal ocean ridge – transform fault systems, otherwise inexplicable.

Finally for convenience, the rules of the long period earth tides to be obeyed in plate tectonics prediction analysis are summarised.

4.2 The Equilibrium Tides

In the equilibrium tides theory it is assumed that the free surface of a body subject to the tide-generating forces at each instant is in hydrostatic equilibrium (i.e. a level surface) under the combined action of gravity, centrifugal force and the disturbing force. If we denote the super elevation due to the tide-generating forces by η_T, we have (see for instance Schureman, 1971):

$$\eta_T = \eta_M \cdot (3/2\cos^2 z_M - 1/2) + \eta_S \cdot (3/2\cos^2 z_S - 1/2) \tag{4-1}$$

where index M = Moon; S = Sun and z = zenith distance, see *Figure 4-1*.

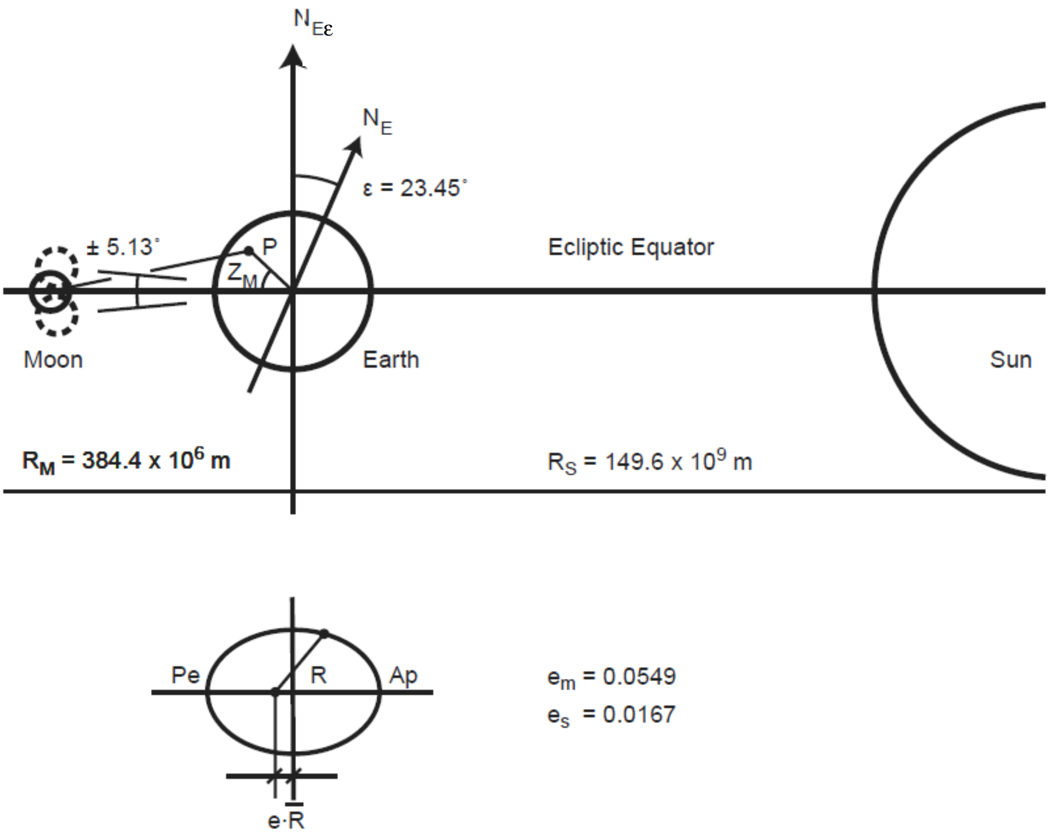


Figure 4-1 Some important figures for the planetary system Sun-Earth-Moon (not in scale): $R_M = R_M$ (average) $(1\text{-}e_M \sin\psi_M)$ and $R_S = R_S$ (average) $(1\text{-} e_S \sin\psi_S)$, where ψ is the argument (phase) of the Moon (index M) and the Sun (index S). The mean longitudes of the orbits are Moon: $s = \omega_M t$; $\omega_M = 2\pi/T_M$; $T_M = 27.321582\ T_E$, and Sun: $h = \omega_S t$; $\omega_S = 2\pi/T_S$; $T_S = 365.256361\ T_E$.

The amplitudes in these deformations are determined by the following relations:

$$\begin{aligned} \eta_M &= \frac{M}{E}\cdot\left(\frac{a}{R_M}\right)^3\cdot(a+b)/2 \\ \eta_S &= \frac{S}{E}\cdot\left(\frac{a}{R_S}\right)^3\cdot(a+b)/2 \end{aligned} \tag{4-2}$$

where M = mass of the Moon (M = E/81.3), E = mass of the Earth, S = mass of the Sun (S = 333,000 E) and R is the varying centre to centre distance between Earth and Moon (index M) and between Earth and Sun (index S), respectively and (a+b)/2 is the average radius of the Earth, see *Figure 4-1* and *Figure 4-2*. In numbers the minimum-maximum values are η_M = 0.304 m - 0.423 m and η_S = 0.156 m - 0.173 m, respectively.

a)

b)

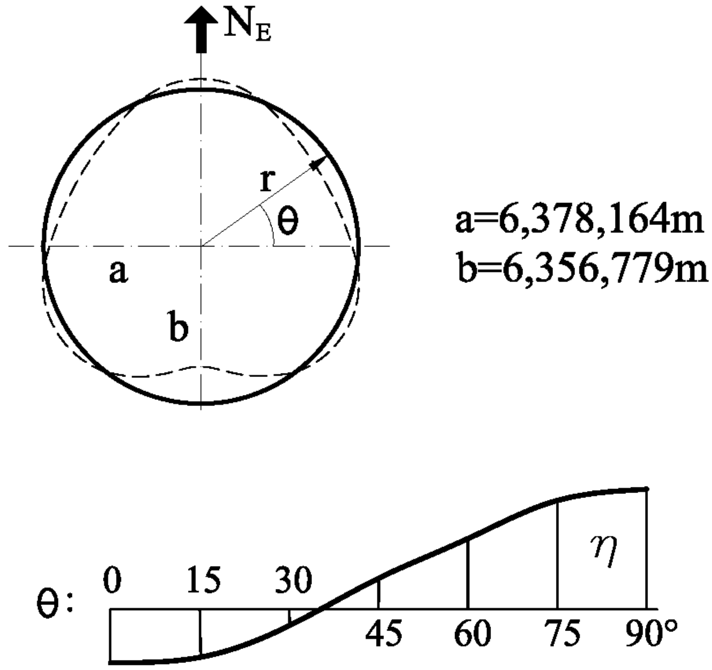


Figure 4-2 *__a)__ The main figures for the first order Geoide (solid line), the best fit of the shape of the Earth to an oblate spheroid (based on satellite tracking calculations (Nicolson, 1977): $r = a\,(1\text{-}0.97078\ \omega^2/g\ a\ \sin^2\theta)$ and $\omega = 2\pi/T_E$; T_E = 86164.1 s; g = 9.82 m/s^2. The broken line shows the height of the present day's Geoide (or see level surface) averaged over all longitudes. The departure from the oblate spheroid is greatly exaggerated. (A more accurate drawing can be seen in Fowler (2009)).*
__b)__ The deviation η from a circle of the cross section of a median in the first order Geoide (from Equator to the Pole). The circle has been cut and stretched into a line in the drawing. $\eta = 1/3\ 0.97078\cdot\omega^2/g\cdot a^2\cdot(1\text{-}3\ \sin^2\theta)$.

Equation (4-1) above, which represents the principal vertical super-elevation of the Earth due to the lunar and the solar tide-producing forces, can be expanded into a series of harmonic terms (Schureman, 1971). By doing so the zenith distance z (see Equation (4-1)) of the Moon and Sun can be expressed in terms of the latitude of the observer (θ), the declination of the Moon and Sun (D) and the hour angle of the Moon and Sun (t) relative to the observer. For the lunar component one obtains (see Equation (32) in Schureman, 1971):

$$\begin{aligned}\eta(\theta,D) = \eta(0,0)\cdot((1/2-3/2\cdot\sin^2\theta)(2/3-2\cdot\sin^2 D)+\\ \sin 2\theta\cdot\sin 2D\cdot\cos t+\cos^2\theta\cdot\cos^2 D\cdot\cos 2t)\end{aligned} \tag{4-3}$$

A similar expression is obtained for the solar component. This reformulation separates the equilibrium tides into three parts, which constitute the basic for the correlation paradox.

4.3 The Paradox of Plate Tectonics and Earth Tides Correlation

The two last terms in Equation (4-3) represent the diurnal (lunar day) and semidiurnal constituents, respectively. These two terms, associated with the daily rotation of the Earth, yield by far the greatest contributions to the equilibrium tides. Nevertheless, there is proven evidence for these terms being of insignificant importance for earth quakes and hence for plate tectonics.

The first term represents the so-called long period constituents, that is to say the constituents with periods somewhat longer than a day and in general half a month or longer. This term is due to the orbital motion of the Moon and the Sun, and represents the smallest contribution to earth tides, but paradoxically many convincing articles have demonstrated a significant correlation between earth quakes and these longer periods. Hence, long period earth tides must have an effect on plate tectonics, but as it is not the insignificant earth tides stresses themselves, which provoke the tectonic plates, some sort of catalyst effect has to take place. Hence, a throughout analysis of the effect of long period earth tides on plate tectonics is pertinent in order to identify the catalytic converter effect, which may explain the paradox.

One notices that the long term constituents are independent of the rotation of the Earth (i.e. independent of the hour angle (t) alias the longitude), but dependent of the latitude (θ). Furthermore they are subject to variations arising from changes in the declination (D) of the tide-producing object (Moon and Sun). The term containing the declination of the tide-producing body (D) can be further expanded by introducing the astronomical data describing the orbital motions of Earth, Moon and Sun. Substituting these values into the term representing the long period constituents yield the decomposed contributions to the long period equilibrium tides shown in *Table 4-1* (see Schureman, 1971).

Symbol	**Period**	$\eta_{ET} = 0.6 \cdot \eta$	**Net equatorial plate spreading**	
	[year]	**[mm]**	**[mm/stroke]**	**[mm/year]**
MN	18.6	-5.2	65	4
SA	1.0	0.9	11	11
SSA	0.5	5.8	73	146
MSM	0.0871	1.3	16	188
MM	0.0754	6.6	83	1100
MSF	0.0404	1.1	14	342
MF	0.0374	12.5	157	4200
FN	0.0374	5.1	64	1714
MT	0.025	2.4	30	1206
MTT	0.025	1.0	13	503
Sum of all				**9414**

Table 4-1 The equatorial circumference lengthening as caused by the long period earth tides constituents. The contribution from a constituent amounts to 4 π η_{ET} per stroke (times the Love number 0.6). The last column yields the yearly contribution from the single constituents by multiplying the stroke value with the number of strokes per year. The total yearly potential for sea floor spreading amounts to 9.4 m, which is two orders of magnitude higher than the sea floor spreading observed. This shows that the potential in the earth tides to move the plates is great. Abbreviations are standard: M = Moon, Monthly; S = Solar, Semi; A = Annually; F = Fortnightly; T = Tertial. The numbers are from Schureman (1971). The numbers can also be found in www.en.wikipedia.org/wiki/Earth_tides (in a condensed form), where the amplitudes mean the peak to peak deformations.

There are three important properties to emphasise on the long period constituents in the equilibrium tides in *Table 4-1*, see *Figure 4-3*. First of all the deformations are rotationally symmetric (i.e. independent on the longitude) and hence global, contrary to the diurnal and semi-diurnal constituents which are dependent on the longitude and therefore local. Second, the deformations are symmetric about the equatorial plane, i.e. identical north and south of Equator. Third, the amplitudes vary with the latitude θ in such a way that the volume of the Earth is kept constant, which implies that the surface area of the crust is time varying, see below. See also Wikipedia (www.en.wikipedia.org/wiki/Earth_tides). Note that the numbers in *Table 4-1* can be found in a condensed form in the same www, where the amplitudes mean the peak to peak deformations.

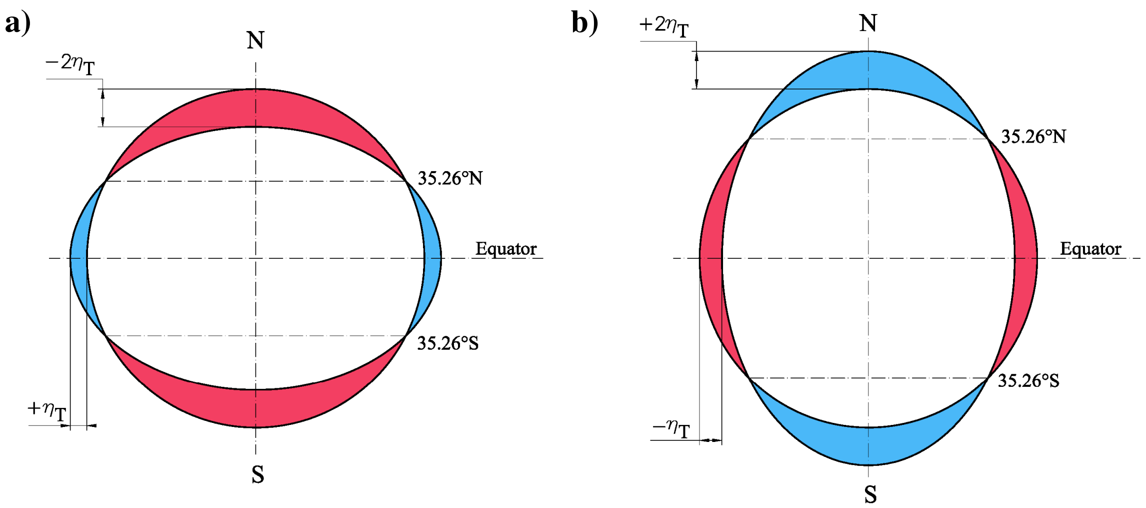


Figure 4-3 A meridian cut through the Earth. The diagrams (not in scale) illustrate the deformations of the Earth due to one of the constituents in the long period earth tides. The deformations are rotational symmetric and symmetric about the Equator plane. See also Figure 1-2.
***a)** The half cycle period with elevation of the equatorial belt (blue color) and lowering of the two polar skullcaps (red color).*
***b)** The half cycle period with opposite deformations.*

4.4 The Equatorial and the Meridian Circumference Shortening and Lengthening

The radius of the equatorial great circle is due to the earth tides varying around its average value with plus and minus η_{ET}. At the latitude θ = 35.26° N and S the long period earth tides become zero (see Equation (4-3) above). At higher latitudes the super elevations change sign. The meridian great circles (through the poles) are at the same time deformed into an oblate ellipse with the deformation of the major axis (a) of +/- η_{ET} at Equator and a (reverse) deformation of the minor axis (b) of -/+ $2\eta_{ET}$ at the Poles. Hence, when the belt around the Earth limited by the latitudes 35.26° N and S experiences a lengthening due to a positive super elevation, the belts located at higher latitudes are subject to a simultaneous shortening of the length.

When the radius of the great circle along the Equator changes from (a - η_{ET}) to (a + η_{ET}), the circumference is increased by the length $4 \cdot \pi \cdot \eta_{ET}$. Because the elevations due to earth tides are a function of the latitude, the maximum minus the minimum length varies with latitude. The mathematics is to find the components of the super-elevation in the Equator plane, i.e. to multiply the product by cosθ. Hence, the circumferential change rate along a constant latitude is equal to the equatorial value times (1 - 3 $\sin^2\theta$) $\cos\theta$. The function is illustrated in *Figure 4-4* and discussed below.

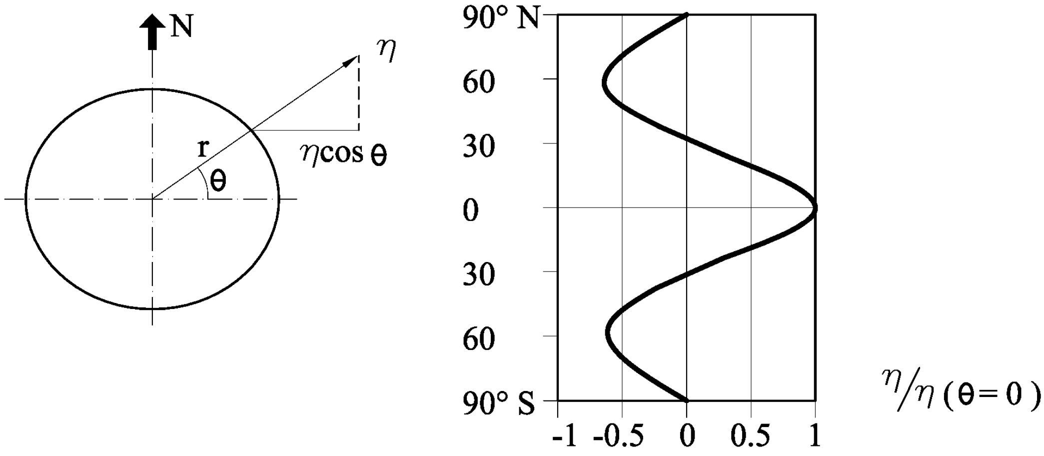


Figure 4-4 The theoretical earth tides generated circumferential spreading rate η along constant latitude as a function of latitude. The wedge effect of the spreading ocean plates will smooth out the curve (corresponding to a moving average):
$\eta(\theta) = \eta_{ET}(\theta=0)\ (1 - 3\sin^2\theta)\cos\theta$.

Similarly, the changes of the length dl along the meridian circumference (through the poles) are varying with the latitude θ as:

$$dl = \eta_{ET} \cdot (1 - 3 \cdot \sin^2\theta) \cdot d\theta \qquad (4\text{-}4)$$

when subject to an elevation of η_{ET}.

The total lengthening from Equator to 35.26° N can be found by integrating Equation (4-4) to yield $0.40\eta_{ET}$. Hence the Equator-near eastern plus western part of the median lengthening amounts to 4 times this value, i.e. $1.6\eta_{ET}$ or $3.2\eta_{ET}$ for a peak to peak variation. This amounts to approximately 1/4 of the lengthening along the Equator circle for the same peak to peak variation.

The simultaneous shortening of the median length for the two Polar Regions is found by integrating Equation (4-4) to yield $4.7\eta_{ET}$ or $9.4\eta_{ET}$ for a peak to peak variation. This amounts to 3/4 times the lengthening along the Equator circle for the same peak to peak variation.

4.5 The Catalyst Effect of Long Period Earth Tides on Plate Tectonics

In the half cycle period of extension and compression, respectively, the Equator near belt of the Earth experience a simultaneous lengthening and shortening of the surface which is varying with latitude (see *Figure 4-4*) but uniform along constant latitude and varying along a meridian (see *Figure 4-2b*). The maximum deformations are at Equator; at latitudes 35.26° S and N they are zero. At the two polar skullcaps the reactions are the same, - just 180° out of phase, and now with maximum deformations at the two Poles, see for instance *Figure 4-3*.

As a frame of reference for the following analysis we take the structure of the ocean plates as observed, i.e. with a zigzag mid-ocean ridge system, where the extensions of the ridge-ridge transform faults, the ocean fracture zones split up the ocean plates in relatively narrow stripes. Depending on the ocean we look at, the orthogonal ridge transform fault pattern run nearly either north-south or east-west as expected when long period earth tides are the ruler of plate tectonics.

The cause of the ocean fracture zones is the shear stresses put on the relatively thin ocean lithosphere. The east – west going ocean fracture zones are orthogonal to the north – south going mid-ocean ridges and hence the fracture zones are caused by the latitudinal variation of the earth tides generated sea-floor spreading, see *Figure 2-2*, an example from the Atlantic Ocean. The north – south oriented ocean fracture zones (orthogonal to the east – west going mid-ocean ridges) are caused by a longitudinal variation in the forces moving the ocean plate. An example is the Somalian Plate and the Antarctic Plate, see *Figure 4-5*, where the western part is slowed down compared to the eastern part due to the collision with the Eurasian Plate.

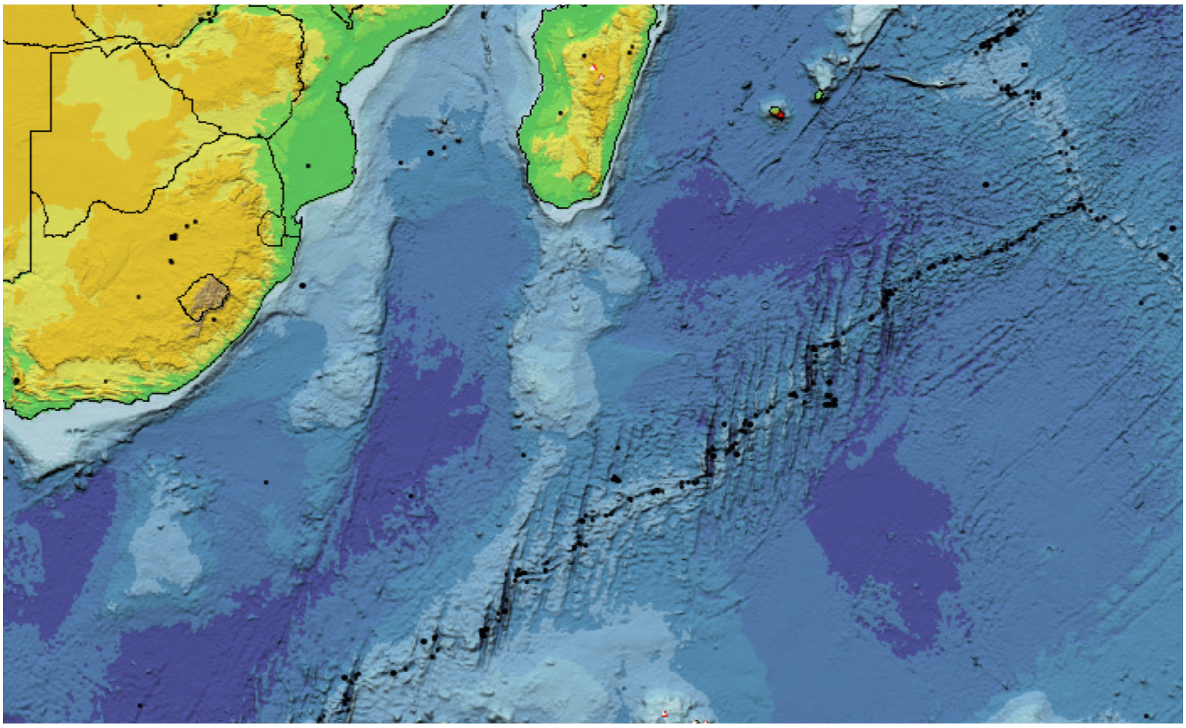


Figure 4-5 Typical north-south running fracture zones in extensions of the ridge-ridge transform faults. Here an example from the Somalian Plate and the Antarctic Plate, see also Figure 2-1. Adapted from MAP (1994).

The rigidity of the continental lithosphere allows the plates to transmit shear stresses during geologic time. This implies that the latitudinal variation in the east – west stretching – compression by earth tides is relaxed by elasticity and hence no fracture zones are to be found on the continent. One notice that around 35.26° N where the variation and hence the earth tide generated shear is maximum is a so called diffuse boundary zone on the huge continent of the Eurasia Plate (*Figure 2-1*), i.e. a broad belt in which deformations occur over a wide range. The lack of such a zone on the symmetric latitude 35.26° S is of course that no major continents are located at this latitude. The longitudinal variation in the forces moving the plates may create north – south going transform faults, such as the famous San Andreas Fault in California.

To investigate the suggested catalyst effect of the earth tides on plate tectonics, the impact from one of the harmonic constituents in the long period earth tides is followed through one cycle. It was shown that the long period earth tides super elevations are rotational symmetric, which imply an evenly distributed super elevation along for instance the Equator circumference of the Earth. Hence, during a half cycle the minimum to maximum length along the Equator is changed $2\pi\cdot$(peak to peak elevation). The chosen object of investigation is an equatorial ring of the outermost part of the Earth (the lithosphere), which consist of quasi-solid plates separated by diverging, converging and/or fracture-transform zones. First the half cycle with lengthening is considered, second the following half cycle with shortening.

The first response to the starting lengthening of the circumference would be an elastic deformation with associated horizontal tension stresses in the crust and in the mass below (the lithosphere). The chosen equatorial ring has a uniform deformation and hence it has to obey the force balance constrain, namely that the pulling force is the same all along the ring. This is the key that solve the paradox of long period earth tides as the driver of sea-floor spreading. Notice that the medians do not have a force balance constrain because the deformations are varying with latitude.

Take for the sake of argument that the zones of ocean ridges and transform faults-fracture zones have a capability to withstand tension stresses, which compared to the zones of the quasi-rigid part of the lithosphere plates is x times less. The precise values of the factor x (different for different locations and fracture types) is not known, but it can be concluded safely that the major part of the lengthening takes place at the tension-weak ocean ridges, transform faults and fracture zones. A line orthogonal to the ridges is only crossing a few tension weak zones and hence the openings become significant at the ridges (MAP, 1994). A line parallel to the ridges does cross numerous tension weak zones, and hence the openings become very small at the transform faults and the ocean fracture zones. The relatively thin lithosphere and the underlying ductile magma chamber at the ocean ridges cause the major part of the lengthening to take place here, i.e. a prerequisite for sea-floor spreading. In *Table 4-1* values for the potential net equatorial ridge opening rate [mm/year] are outlined, simply by multiplying the half cycle lengthening $2\pi(2\eta)$ with the number of cycles per year. Although the contribution from the single cycles of super elevation is moderate, the sum is in no way insignificant (more than 9 m/year). The increases in the potential volume for the magma chamber let hot mantle rock ascend to fill the gap, see *Figure 4-6*. The temperature of the ascending rock is nearly constant, but the pressure release in the magma (due to the tension) decreases the solidus temperature (the temperature at which the rock first melts). According to Turcotte and Schuberts (2007), the rock which is produced by partial melting beneath an ocean ridge is lighter than the residual mantle rock, and hence buoyancy forces drives it upwards in the magma chamber towards the surface in the vicinity of the ridge crust.

In the following half cycle period shortening of the length takes place. During this period with compression the plates will move back towards the original position. The compression increases the solidus temperature and combined with heat loss to the seafloor, part of the magma solidifies to form the new ocean crust at the ridge. The solidification of magma in the ocean ridge fissures is enhanced by the effective hydrothermal heat exchange in the porous mid-ocean ridge crust (Fowler, 2009). Hence, a small net sea-floor spreading takes place at every stroke. The start equatorial length is obviously retained, which imply compensation by either slab subduction or mountain folding. Based on paleomagnetic analysis dating, the net spreading rate of the plate’s amount to the order of magnitude of 10 to 100 mm/year. This spreading rate is less than 1% of the yearly sum of fissure openings due to earth tides. Such a low efficiency in the sea floor spreading due to earth tides could be expected, because flow and solidification of magma takes time and the greatest contributors to the lengthening just stems from the most fast and hence less effective constituents in this respect. It is concluded that the movements caused by the long period constituents in the earth tides has the potential to work as an effective catalytic converter for sea-floor spreading. Hence, the long period earth tides acts as a slowly, but persistent and strong pulsating *dynamic* ridge push engine (not to be confused with the moderate hydrostatic ridge push), which contributes to plate tectonic.

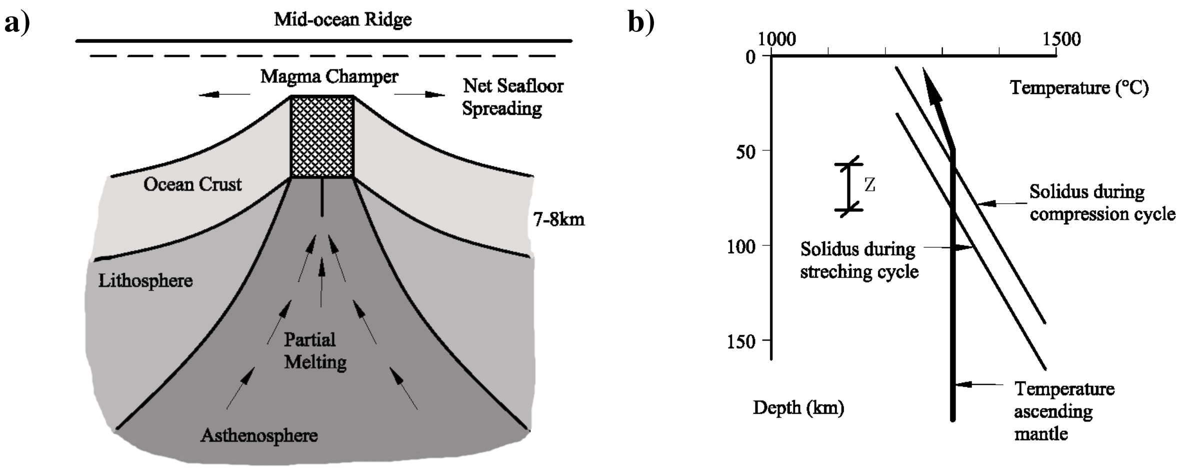


Figure 4-6 ***a)*** *Sketch of the ascending, partial melting mantle, which fill the gaps created during the stretching cycle of earth tides (not in scale).*
b) *The solidus temperature (temperature at which the rock melts) versus depth are illustrated for the compression cycle (increased pressure) and the stretching cycle (reduced pressure) of the earth tides, respectively (not in scale). A cyclic production of melted rock occurs in the interval denoted z in the figure. z is the maximum pressure difference between the compression cycle and the stretching cycle, measured in km rock column (highly exaggerated for the sake of illustration). Part of this melted rock rise due to buoyancy.*

Of course the capability to withstand tension stresses varies with time along the ridge. This implies that the plate divergence may happen in discrete places and episodes separated by say tens or hundreds of years any one place. One observation of this behaviour has been observed at the Krafla Volcano, Iceland (Tryggvason, 1984), see *Figure 4-7*.

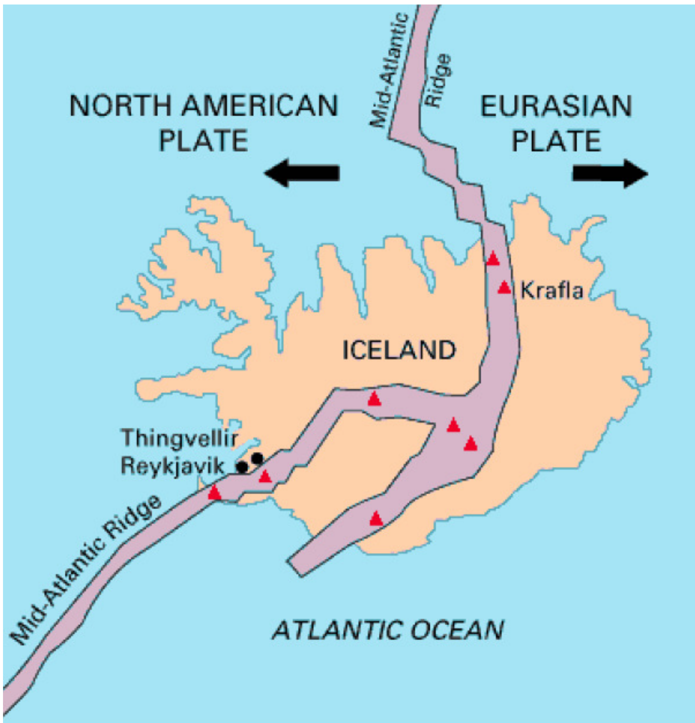


Figure 4-7 *Map showing the Mid-Atlantic Ridge splitting Iceland and separating the North American and Eurasian Plates. The map also shows Reykjavik, the capital of Iceland, the Thingvellir area, and the locations of some of Iceland's active volcanoes (Δ), including Krafla. Adapted from Kious and Tilling (1996).*

The Mid-Atlantic Ridge goes across the volcanic country Iceland, creating an accessible observation area of the processes going on in the ridge zone on a short timescale. The Krafla Volcano in the north-eastern part of Iceland is located in an active fissure zone, where new cracks are created and old ones widened occasionally within a few month. During the period 1975 to 1984 this rifting resulted in a net spreading of about 7 meter, which is considerably more than the average sea-floor spreading rate of the Mid-Atlantic-Ridge (20-25 mm/year). At this latitude, the potential opening of the ridge caused by earth tides amounts to approximately 5.6 m/year (the equatorial value times $(1 - 3 \sin^2\theta) \cos\theta$), which is nearly 10 times the observed spreading. Hence the earth tides have the potential to create this order of magnitude rifting. One could for instance imagine that part of the intruded material in the fissures opened by the earth tides is accumulated in the huge magma chamber associated with the volcano and then by buoyancy forces is transported towards the ground in time with the succeeding openings. The limited 9 years of time span for the event combined with the actual observation of a gradually 1 to 2 m lifting of the ground followed by a sudden dropping before the creation of new cracks could indicate the scenario outlined above, but other explanations are possible. The overall objective of mentioning this particular event is to emphasize that earth tides have the elements needed for a plausible explanation for this sort of local great abrupt rifting, while the other sea floor spreading mechanism do not offer a similar straightforward explanation for such huge local surface cracking. In Iceland the oceanic crust is sufficiently thick so that the ridge crest rises above sea level (the isostatic equilibrium). Therefore the local plate behaves more like a rigid continental plate which imply that the great shear stresses created by the huge opening of a limited length are relaxed elastically during geologic time. In this way, as one moves away from the ridge the net effect on the spreading plate is one of continuous movement of only 20-25 mm/year.

To confirm the hypothesis of earth tides being an important factor in plate tectonics, a catalogue of confirmatory observation reported in the literature is briefly summarised.

After confidence to earth tides as the universal driver in plate tectonics hopefully has been consolidated by the confirmatory examples, the rules of earth tides are summarized for convenience and then used in the succeeding reconstruction of the history of the continents.

4.6 Observations related to Earth Tides

The following discussion starts with an observation of the movement of the African Plate, which points towards the earth tides being the top candidate for the spreading of the Mid Atlantic Ridge. Then follows a catalogue of reported observations related to earth tides.

4.6.1 Slow down of the African Plate

An example of a spectacular event, where the three different candidates for plate movement yield totally different answers on the consequences for plate tectonics, is the observed slowdown of the north-east-ward absolute motion of the African Plate some 30 million years ago (after the contact with the Eurasian Plate) (Silver et al., 1998). Therefore this event is well qualified for a test of the theories.

Neither the African Plate nor the adjacent South American Plate has a subducting slab, and hence no slab pull can create sea-floor spreading between them.

According to the convection theory the African Plate was slowed down due to the arising counter pressure in this collision. The movement of the adjacent South American Plate should have been unaffected since the velocity in the driving convection cell below this plate is governed by the unchanged heat flow from the interior and by other unchanged properties.

Therefore, the sea-floor spreading at the Mid-Atlantic Ridge should consequently have slowed down with the same rate as the slowdown of the African Plate motion.

The collision of the African Plate with the Eurasian Plate did not change the physical characteristics of the number and the size of the plates and the ridges located along those circumferences around the Earth, which are cutting the two plates. Hence, the earth tides generated ridge opening, succeeding solidification of intruded magma and the resulting sea-floor spreading of the Mid Atlantic Ridge should be unchanged if earth tides are the driver of plate tectonic.

The observations showed an unaffected sea-floor spreading rate at the Mid-Atlantic Ridge (nearly constant during the last 80 million years) and consequently a simultaneous westward acceleration of the South American Plate. The unchanged spreading rate and the westward acceleration of the South American Plate are in contradiction with the convection theory, while the behaviour observed is as expected if earth tides are responsible for the plate movements. Hence, this example shows that earth tides is a worthy candidate in plate tectonics.

4.6.2 Neutron radiation in seismic regions

Recently, Russian physicists observed that at new moon and full moon periods the intensity of neutron radiation sharply increased in the areas of seismic activity (Volodichev et al., 2000). This led them to analyse global data of earthquakes that occurred from 1964 to 1992 and from this analyses they found a two-week periodicity connected with the full and the new moon phases. The fortnightly variation of the neutron radiation in seismic active regions supports the assumptions made here that the tidally generated expansions and contractions are concentrated to the seismic active regions and are associated with the slowly varying long period constituents of the earth tides (i.e. with periods of a fortnight or more).

4.6.3 Strong correlation's of earthquakes at widely separated regions

Chinnery and Landers (1975) constructed time series (covering several years) of earthquakes with magnitude greater than a chosen threshold. The time series from widely separated regions show strong correlation's with one another. This led them to the conclusion that external effects, such as changes in the rate of rotation of the Earth and tidal stresses, must be important here. The earth tides theory presented above contains a more realistic suggestion for an external effect, which has the world wide strong correlation observed.

4.6.4 Oblique subduction of tectonic plates at trenches

It has been noted that earthquake-generating slip directions do not always coincide with the local plate convergence vector, indicating that the resulting plate movement is the sum of at least two movements in different directions. DeMets (1995) found that the oblique convergence sometimes is partitioned into two components, one directed more orthogonal to the local strike of the trench than the local plate convergence vector, and the other directed parallel to the local strike of the trench. This description agrees with the two principal deformation directions of earth tides deformations.

4.6.5 Correlation of earthquakes with earth tides

If earth tides has a pronounced impact on plate tectonics and plate tectonics generates earthquakes, it is natural to expect that earthquakes can be correlated to earth tides. Many investigations of the possibility that earth tides are a triggering factor of earthquakes have been reported in literature, e.g. Allen (1936), Chimnery and Landers (1975), Bodri and Iizuka

(1989), Weems and Perry (1989), Amdeh and Fairhead (1991), Patane et al. (1994), Souchay and Stavinschi (1997), Vidale et al. (1998), Enescu and Enescu (1999), Lockner and Beeler (1999), Volodichev et al. (2000) and Perfettini and Schmittbuhl (2001) to mention a few. The investigations show that tidal triggering of earthquakes only seems to be a possibility in some cases, but even then it is very difficult to detect. Most authors has failed to find a firm correlation, because they have focused on the apparently most important strong semi-diurnal and diurnal constituents, which as pointed out in the present analysis on earth tides have no effect on plate movements and hence neither on the associated earth quakes. As argued above the much weaker long period constituents are the candidates. The forcing function for the plate movements is therefore based on a sum of many different harmonics, which makes a harmonic analysis a more time-consuming and difficult task. Another complication is that the physical properties of the magma and the crust constitutes the transfer function from the earth tides movements to the plate movements, which may imply different phase lags for the different harmonics. Anyhow, in an analysis it is worth to remember the 180 degree phase lag between the lengthening and shortening cycles of the areas located within +/- 35.26° latitude and the areas located outside this belt.

4.6.6 Observed plate movements for diurnal and semi-diurnal versus long period constituents

It is interesting to recall the observations made by Bilham et al. (1999) from the rift zone between the Somali and Nubian plates (in Africa). Based on 28 years of laser ranging and GPS data they observed a long-term separation velocity of the plates (4.5 +/- 1 mm/year). Nevertheless, they found no amplification of the semi-diurnal strain tides across the rift, indicating that the low rigidity of the rift zone apparently only applies for the long period impact in agreement with the assumption made in the present article. All the elastically tidal stress fluctuations are very small. It is therefore not likely that the semi-diurnal and/or the diurnal earth tides in general should be able to be a triggering factor of earthquakes. This has been nicely demonstrated by Vidale et al. (1998) who analysed the tidal stresses and stress rates on the San Andreas and Calaveras fault planes. At the times of 13,042 earthquakes they found stresses and stress rates from earth tides distributed in the same way as tidal stresses and stress rates at random times. In summary, semi-diurnal and diurnal earth tides have in the general case probably very little direct and/or indirect consequences for plate tectonics and earthquakes.

4.6.7 Correlation of earth quakes to the long periods in earth tides

According to the hypothesis presented, one condition for a successful correlation between earth tides and earthquakes is that one focus on the long period constituents only. An example is the study by Souchay and Stavischi (1997) of earthquakes in the very active seismological zone of Vrancea (Romania, about 46° north). They found that the earthquakes preferentially occurred during the ascending part of the sine oscillation of the tides with periods 18.6 years (MN), 182.62 days (SSA) and 13.66 days (MF). The periods are all in agreement with the periods identified in *Table 4-1*. This significant correlation between earth tides and earthquakes supports the hypothesis of a strong coupling between the long period constituents of the earth tides and the movements of the tectonic plates, and hence it supports the existence of the earth tides ridge push outlined above. The accumulation of stress along a plate boundary means that there is an unknown time lag between the earth tides forces and an earthquake. It therefore can be very difficult to detect the tidal triggering of earthquakes. Because the stress accumulation depends on the geophysical and tectonic characteristics of the area concerned and the tidally generated ridge push is a function of latitude there are good reasons for performing correlation test for only one locality at the time.

4.7 Rules of the Long Period Earth Tides

As has been make probably above earth tides are the universal driver of plate tectonics. The basic results of the analysis gave the following main results, which shall be listed here once for all (with **bold keywords**), as they constitute the universal rules to be obeyed in plate tectonics prediction analysis.

1. **Rotational symmetry**. The deformations due to tide are rotationally symmetric (independent on longitude).

2. **Symmetry about the equatorial plane**. The deformations due to tide are symmetric about the equatorial plane (identical north and south of Equator).

3. **Axes of fracture zones**. The symmetries let to the qualitative prediction that the principal axes of fracture zones, ocean ridges, continental rifts and ocean trenches (subduction zones) statistically must obey the same symmetric constraint as the forcing, i.e. basically they will prefer to run east – west (due to a median stretching) and/or north – south (due to a stretching in a latitudinal plan).

4. **Sea-floor spreading variation with latitude**. The theoretical latitudinal circumferential sea-floor spreading rate vary with latitude θ as follows: rate along constant latitude = the equatorial rate times $(1\text{-}3\sin^2\theta)\cdot\cos\theta$. Due to elastic relaxation this curve is smooth out, see Figure 4-4.

5. **Median sea-floor spreading**. The theoretical median circumferential spreading rate is independent on longitude.

6. **Median stretching variation with latitude**. The actual stretching is zero at 35.26° N and S. It has a local maximum at Equator and at the Poles; the amplitudes at the poles are out of phase and have double the value of Equator's amplitude. The variation is shown in *Figure 4-2b*. Notice that the median stretching can be compensated by an elastic deformation of the plate.

7. **Typical sea-floor spreading rates**. A typical mid ocean spreading rate is 20 to 30 km/My, while the rate for plates with a subducting ocean slab ahead amounts to 60 to 70 km/My.

8. **Subduction and mountain folding caused by sea-floor spreading**. At an equatorial zonal belt, the sea-floor spreading is compensated for either by subduction of an ocean plate or by mountain folding of a continent. Actually the equatorial belt constitutes a special case because of the equatorial symmetry.

9. **Advantageous latitude movement**. In the general case, the lengthening due to earth tides generated sea-floor spreading is bound by some regularity. Zonal belts at other latitudes than Equator, which are subject to an expansion in the east-west direction, have two more options for compensation, the first being to move towards latitudes with divergent meridians.

10. **Formation of new minor-continents**. The other option is to stay at the elevated position letting the other plates in the ring return to the starting position. The last possibility is time limited, as a continuous elevation relative to the neighbor plates eventually result in the lower adjacent plate to be submerged under the elevated plate.

11. **Disadvantageous latitude movement**. When crossing Equator, the meridians convert. Hence, if a plate is pushed against its nearest Pole, it very fast has to create a north-south going subduction zone, because otherwise it cannot compensate for the extra need of compensation.

12. **Meridian rings** do not have the option to move towards a greater circumference to compensate for the added mass in a north-south expansion. They are forced either to create a subduction or to absorb the added mass by mountain folding or local intrusion, or simply to react elastically.

The rules are many and restrictive which means that the degrees of freedom for the driving of the tectonic plates are very limited. Fortunately, this implies that the predictions, where these rules have been obeyed, are very robust! The rules are rather simple, logic, powerful and easy to apply, which shall be demonstrated in the reconstruction process Chapter 5.

5. RECONSTRUCTION OF THE HISTORY OF THE CONTINENTS

5.1 Introduction

As was demonstrated in Chapter 4 earth tides are the universal driver of plate tectonics. By applying the rules of earth tides a reconstruction of the origin, growth, appearance as land, fragmentation and drift of the continents are performed. The reconstruction is divided into 6 epochs as follows:

1. Rotating self-gravitating inhomogeneous masses. Formation of the Geoide.

2. Cooling and formation of crust floes, growing thicker and greater with time. Formation of median and latitudinal fracture zones by earth tides.

3. Creation of the two symmetric subsea Polar Supercontinents, Gondwanaland and Laurasia. The growth rate is calculated and confirmed by observations.

4. First appearance of land at about 600 Ma, a consequence of isostatic equilibrium. Dramatic increase in oxygen content in the atmosphere after that event.

5. The cause of the fragmentation and drift at 160 Ma of the Supercontinents into present day's continents.

6. The continental drift during 160 Ma. The result is an unmistakable picture of present-day locations of Earth's continents, oceans, divergent and convergent boundaries.

5.2 Rotating Self-Gravitating Inhomogeneous Masses

Epoch I. 4550 Ma to 4??? Ma

The Earth started some 4550 million years ago as an inhomogeneous mixture of gasses and other cosmic material. The combined action of gravity and centrifugal forces due to the rotation of the Earth acted as a sort of grader, sorting the masses according to their density. Because the density of the different materials is a function of temperature and pressure, this separation process was disturbed and counteracted, especially by buoyancy driven convection. After the rearrangement of the masses the major internal division of the Earth was probably nearly the same as to day: Solid inner core, liquid outer core, solid lower and upper mantle and finally an outermost hot liquid mass subject to intense convective mixing and cooling. At that time the Earth no doubt was a perfect oblate spheroid, see below.

The reasons for giving a summary of rotating masses are two-fold: As described in Epoch V below this perfect balance is in the time to come gradually upset by the redistribution of mass during the formation of continents, which eventually must have a consequence. Further on, the basic shape of the Earth is the frame for calculating earth tides, as was done above.

Two scientific disciplines originating from the eighteenth century form the basis for the understanding of earth tides, namely rotating masses of liquid (determining the basic shape of the Earth) and tide-generating forces. It started with Newton's prediction of the elliptically Earth. MacLaurin (see Lamb (1932)) solved the homogeneous rotating mass problem. He found the oblate spheroid with flatness (ellipticity) of:

$$f_{hom} = \frac{5}{4} \cdot \frac{\omega^2 a}{g} \tag{5-1}$$

where ω = angular velocity [per sec], a = major axis [m] and g = acceleration of gravity [m/s^2].

Meanwhile, the Earth is inhomogeneous and at present covered by tectonic plates. As pointed out by Lebovitz (1979) one solution to the stable spheroid for an inhomogeneous rotating mass is a mass distribution following the ellipsoidal shape, implying constant pressure along these "pycnospheroids". Hence, we accept the spheroid as the best first order approximation to the initial shape of the Earth. If the present Geoide is fitted to a spheroid, the data shown in *Figure 4-2* are obtained (Nicolson, 1977). Notice that the flatness factor is reduced from 5/4 to 0.97078 (with an average g = 9.82 m/s^2) when the in-homogeneity of the Earth is taken into account. With this value for the flatness, the inhomogeneous Geoide is given by the formulae for the radius-vector r as a function of the latitude θ:

$$r = a \cdot \left(1 - 0.97078 \cdot \frac{\omega^2 a}{g} \cdot \sin^2 \theta\right) \tag{5-2}$$

A convenient alternative illustration of the ellipticity of Earth is to plot the deviation η from a circle with radius a, as shown in *Figure 4-2b*, where the circle of reference has been cut and stretched into a line. If we further correct the deviation to have equal masses above and below the globe of reference (i.e. a dislocation of 1/3·(b-a) of our line of reference), we obtain:

$$\eta = \frac{1}{3} \cdot 0.97078 \cdot \frac{\omega^2 a^2}{g} \cdot (1 - 3\sin^2 \theta) \tag{5-3}$$

As was demonstrated above in Chapter 4, the vertical deformations caused by the constituents in the long period earth tides do have the same latitudinal variation as the Geoide.

5.3 Cooling and Formation of Crust Floes and Oceans

Epoch II. 4??? Ma to 4000 Ma

The sensational discovery by Rosing (1999) of a sediment dated >3700 Ma in Isua, Greenland containing the oldest known fossil microorganism shows that at this early stage in the history of the Earth a life-giving ocean was already established. Hence let us assume that – within a few hundred of millions of years margin – Epoch II ended at around 4000 Ma, i.e. at the end of the Hadean era.

The developments during this period were governed by two physical processes, namely heating from below and cooling from above. The heating and the cooling created convection circulation in the outermost part of the Earth and at the same time the cooling caused formation of quasi-solid crust floes. As shown above, the present convection cells have horizontal dimensions of maximum 2000 times 2000 km^2. During Epoch II the heat flux and hence the convection cells were more intense and therefore probably of a smaller dimension. It is therefore most likely that the dimensions of the crust floes did not exceed the 2000 times 2000 km^2, which imply that the Earth was covered by more than 100 randomly distributed crust floes during the initial crust formation period. The insulation by the quasi-solid crust combined with the persistent heat transfer to the atmosphere resulted in a condensation of the gasses released producing the first ocean. As soon as water was covering the Earth a markedly increase in the cooling rate and the solidification process of the crust was started due to the effective hydrothermal heat exchange in the porous ocean crust near the fracture zones (Fowler, 2009). Hence after the creation of an ocean a rapid thickening of the crust took place, which implied that the forces needed to break up the crust into minor floes were radically increasing. When the crust had reached a certain thickness (probably less than a hundred meter) the floes became aggregated into one unbroken shell covering the whole Earth. At that time no subduction had been established. Similarly, the crust was still located at a constant pressure spheroid, i.e. there were no hydrostatic ridge push.

Without long period earth tides the continuation of the solidification process during this Epoch II would have been a slow thickening of the crust without any sea-floor spreading and without formation of continents, in disagreement with the history as we know it.

In the preliminary reconstruction of Epoch II we ended up with an Earth covered by a more than 100 pieces jigsaw puzzle crust covered by an ocean. By introducing the earth tides another more realistic picture of the reconstruction appears.

During the extension cycle the fracture lines open up in proportion to their weakness. Hence the most tension weak fracture zones become "mid-ocean-ridges" from where the seafloor spreading starts. Initially the north-south going ocean ridges are governed by the latitudinal variation of the openings, i.e. the most dominating seafloor spreading occurs at Equator. At the same time is the numerous ocean fracture zones created. Concurrently with the dominating seafloor spreading at Equator the wedge effect help opening up the adjacent fracture zones. This domino effect continues northwards and southwards until a pole to pole zigzag ridge has been formed. As the ocean crust moves away from the ridge, it cools and becomes increasingly denser implying the well-known sinking of the crust with distance from the ridge. This in turn starts the build up of the hydrostatic ridge push, which – although of minor importance - enhances the seafloor spreading process. Measurements have shown that it takes at least around 100 million years for the moving crust to obtain a density that initiate a subduction into the ocean trench next to the continent. But in Epoch II no continents have been build up. Moreover we haven't explained how the added mass at the ridges are compensated for when no continents are present: Is it by thickening of the ocean plates (for instance by intrusions), by folding of the plates or by creating a convergent boundary where the lightest plate slice over the heaviest plate?

The question: How and where is a continent created is addressed in the next chapter dealing with Epoch III.

5.4 Creation of the Two Symmetric Subsea Polar Supercontinents

Epoch III. 4000 Ma to 600 Ma

The idea of Pangaea (Greak, "all lands"), see *Figure 1-3*, was originally launched by Alfred Wegener in 1915, see the translation of Wegener's book (1966). Although never recognized before his dead in 1930, his idea of drifting continents inspired to plate tectonics and it might be in veneration to him that his idea of Pangaea has been stick to, although the convincing evidences of fossil plants and animals actually only relate either to the southern supercontinent Gondwanaland or to the northern supercontinent Laurasia, respectively. Further on Wegener (and his successor supporters of Pangaea) were deceived by the present day's position of the continents on the Southern Hemisphere being in contact with the continents on the northern Hemisphere. As shall be demonstrated below at the postulated time of Pangaea (about 200 Ma) all the continents on the southern Hemisphere were locked at the South Pole. Hence, from that point of view the finding in the present article of two polar continents which comprise the same continents as Laurasia and Gondwanaland, respectively, does not harass these palaeontology evidences; merely require a rethinking about the climate and the conditions for life in the past at the Poles (or rather north and south of 35.26° latitude). The climate is greatly tightened to the position and the shape of the continents at that time; confer with the present day Gulf Stream which has a beneficial effect on the climate in Scandinavia. The basic frame for such a climate analysis has been outlined here (the locations of the continents).

In here we held to the theory that the continents have grown throughout geological time, being derived from the material in the Earth's mantle. According to Turcotte and Schubert (2007) basaltic magma from the mantle that intrudes into basaltic continental crust in presence of water can produce the granitic rock associated with the bulk continental crust. This is in accordance with our finding below that the major part of the continents is created under a cover of water. Moreover the continents are protected against the weather, which implies that in the present model is loss of sediments into the mantle at subduction zones of minor importance. Furthermore we notice that modern Earth Science recognise that the present continents are build around cores of extremely ancient rock, called "shields" (Fowler, 2009).

Therefore the necessary conditions for building up a granitic continent are:

1. The existence of a subsea crust with fracture zones where the long period earth tides can create an accumulation of mass.

2. The crust is locked at a location where the only possible compensation for the mass added are either mounting folding or intrusion into the volume locked, i.e. no subduction into the interior of the Earth is possible and no advantageous movement towards divergent meridians (greater periphery of the Earth) is possible.

In the end of Epoch II the Earth was covered by a fractioned crust, where an unknown number of zigzag pole to pole going ocean rifts were created by the long period earth tides east-west going increasing and decreasing latitudinal circles. The north-south going extension-compression of the median ellipse is varying with the latitude as shown in *Figure 4-2b*, i.e. zero at 35.26° N and S, and out of phase in the high and the low latitudes, respectively. Hence from a physical point of view no force constrain (such as the one applied before for the latitudinal rings, namely requiring an equal force in the ring) can be argued and hence the medial extension might either be by an elastic deformation or by opening an east-west going rift creating a north-south going sea-floor spreading. To handle these two unknown parameters in the reconstruction process, we apply a sort of hind cast guess, i.e. we make an assumption of the development based on what we observe at present time and from that we set up a conceptual model. Then by applying the rules of the earth tides, we calculate the implication of our assumptions and compare the forecasted final result with the known conditions of present day's Earth. In case we end up with a "perfect" final result, we take our assumption for correct. This method is actually always used by other authors dealing with reconstruction of the history of the Earth. The difference in method is that we use physically confirmed rules in the forecasting process.

5.4.1 The conceptual model based on a hind cast

To avoid the visual disturbance caused by minor irregularities due to heterogeneities in the mass of the Earth, the predictions are illustrated by use of sketched idealised, conceptual models. This method yields a clear picture of "what happens where and why", but it actually turns out to give a surprisingly detailed prediction of even some peculiar land formations and of the location of subduction zones, the reminiscence of which can be recognised on the Earth even today.

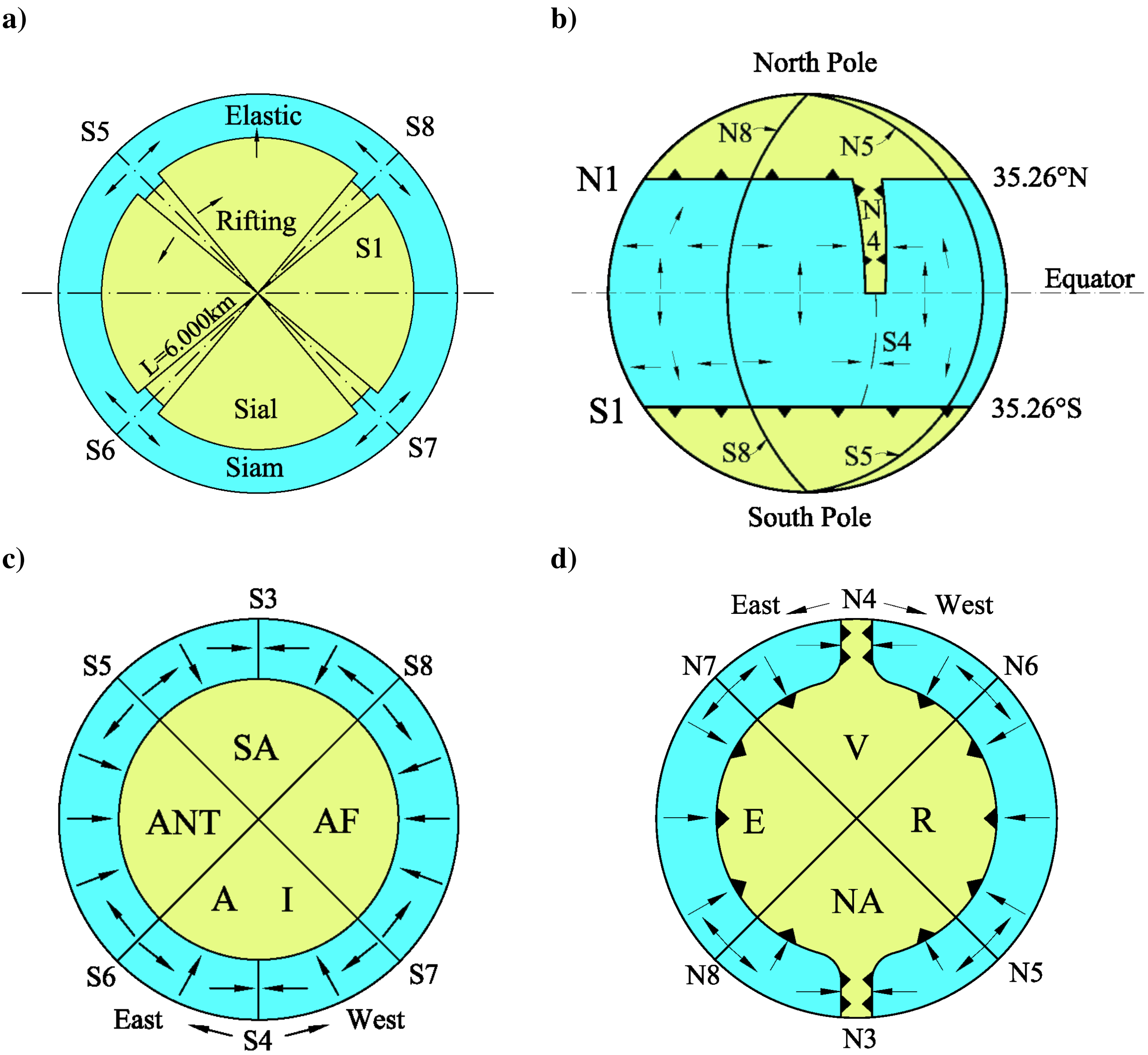


Figure 5-1 Conceptual model of the super continents and the fracture zones.
a) *The South Pole super continent with its northern boundary (S1 = 35.26 ° S), the 4 symmetrically distributed rifting fracture zones. The median response to the earth tides is elastic. Sial is the continental plates, Siam the ocean plate.*
b) *View A (see Figure 5-1c&d) from Equator plane. N1 and S1 are the boundaries for the polar super continents. N4 is a peninsula (Central America) with double sided subduction, see text.*
c) *The South Pole super continent. S3 and S4 are double sided subduction zones. S5, S6, S7 and S8 are the 4 rifting fracture zones envisaged, separating* ***SA*** *(South American Plate),* ***Af*** *(African Plate),* ***AI*** *(Australian-Indian Plate) and* ***ANT*** *(Antarctica Plate).*
d) *The North Pole super continent. N3 and N4 are peninsulas with double sided subduction zones. N5 and N8 are the 2 rifting fracture zones envisaged, separating* ***EUR*** *(Eurasian Plate) and* ***NA*** *(North American Plate).*

The conceptual model sketched in *Figure 5-1* is based on the following arguments:

- Condition 2 above of a locked location of the initial crust can only be fulfilled at the two poles. The demarcation lines where no deformations occur (neither in a circle of latitude nor in a median circle) are at +/- 35.26° latitude and hence these lines, designated S1 and N1, respectively define the foundation for the two polar skullcap supercontinents.

- The area of two skullcaps on the Earth limited by 35.26° latitude amounts to $2.16 \cdot 10^{14}$ m^2. This area is in perfect agreement with the known area of the present days continents including their shelves (which are just continents covered by shallow water), namely $2.01 \cdot 10^{14}$ m^2 (Fowler, 2009). Further on the landmasses of the continents originating from the southern and northern supercontinents amounts to 47% and 53%, respectively (Fowler, 2009), i.e. the symmetry about Equator is confirmed as well.

- Inspection of the jigsaw puzzle with the present continents on the Southern Hemisphere (see *Figure 5-2a*) help us to define the divergent fracture zones at the southern supercontinent, because they have a permanent position during the continent formation period. On the southern supercontinent the number of median fracture zones is determined to be 4, designated S5, S6, S7 and S8, separated 90° from each other and hence rotational symmetrically distributed. This yields an equatorial tide generated sea floor spreading of the order of magnitude of $4 \cdot 30 = 120$ mm/year. On the northern supercontinent the movements have been much more moderate, and hence it serves no purpose to try to move around the continents, because a single glance on the present positions (see *Figure 5-2b*) combined with the knowledge of the locations of the diverging axis at once convinces one about the pre-existence of the northern polar supercontinent. Two median fracture zones seem more likely here. They are designated N5 and N8 as they coincide with the same numbers at the southern supercontinent.

- There are no fracture zones along a circle of latitude in the polar skullcaps, which means that the north – south going tidal deformations are purely elastic here.

- Probably the warm Equatorial Ocean (the Tethys Sea) were recycling its oceanic crust in the same way as oceanic crusts do it in present time, with subduction zones located around the Earth along the supercontinents. The subduction is caused by the observed fact that the oldest oceanic (say more than 100 million years old) crust is located far below the continent by isostatic reasons. Because the polar supercontinents are locked, the scenario outlined prevails during billions of years. During all these years a continuous drift of the diverging ocean ridges take place towards the subduction zones as indicated by arrows in *Figure 5-1* (the arrows are not drawn in scale). When ingested here a new cycle for the sea floor spreading starts, repeating it every 150 to 200 Million years. It has no interest whatsoever to persecute the ocean processes during the next billions of years as it has all sink into oblivion. It is much more relevant to calculate the thickening of the supercontinents as done below.

- A glance on the present day's continents on the northern Hemisphere could indicate that during the continent formation process the whole southern boundary was one unbroken conversion zone with subducting ocean plates. Part of these subduction zones has later on been override by the north going continents from the southern Hemisphere and hence they are invisible to day. One example confirming this is the deep thick high-velocity P-wave regions associated with the India-Eurasia collision, which are most probably subducted oceanic plate now in the lower mantle (Fowler, 2009). Therefore during the time of growth of the supercontinents apparently there has been a north going ocean plate movement intensified by the slab pull in front of the plate.

- There are no indications of a similar unbroken conversion zone at the border of the southern pole supercontinent. This does not mean that this border was not a subducting conversion zone, merely that the later protrusion of the fragmented southern continents into the equatorial ocean have destroyed the subduction zones in the same way as the subduction zone along the North America coastline is gradually destroyed today by the west going North American Plate (see below).

- Based on the observations mentioned above, it is most likely that a mid ocean ridge was formed near Equator creating a north and a south going sea floor spreading, intensified by the slab pull ahead. This disadvantageously movement of the ocean plates towards converging median circles, combined with the east-west going sea floor spreading due to the pole to pole fracture zones, immediately creates a need for north-south going subduction zones.

- On the northern Hemisphere two peninsulas are envisaged (N3 and N4) based on the present day's outlook, where N3 is the southern part of the North American Plate (Central America) and N4 is the south eastern corner of the Eurasian Plate. These peninsulas, which are going from the continent all the way down to Equator, i.e. to the demarcation line between advantageous and disadvantageous plate movement, are subducted by the interjacent ocean plates to compensate for the added mass. A proof for this interpretation is given below, when dealing with the bend of the Hawaiian – Emperor Seamount Chain.

- Due to the later override by the fragmented southern Hemisphere continents a picture of the former subduction zones on the southern Hemisphere is not as clear here. We will elaborate a little on this problem in the epoch dealing with the reconstruction of the latest 160 Million years, because it is of no importance for the creation of the two polar supercontinents.

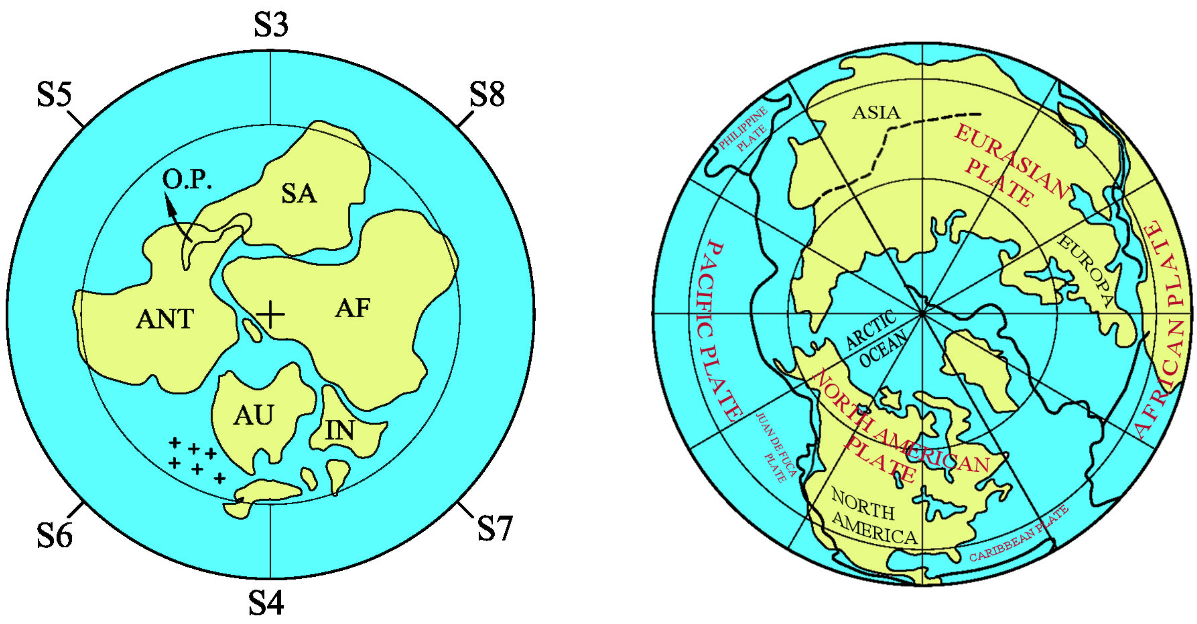


Figure 5-2 ***a)*** *Jigsaw puzzles with the present day's continents on the southern Hemisphere. OP means original position. The letters, numbers and abbreviations used are explained in the text. The theoretically determined boarders of the continents (latitude 35.26°S) are drawn.*
b) *Present day's continents on the northern Hemisphere.*

5.4.2 The gradual thickening of the supercontinent crust

The east-west tide generated opening-closing of the fracture zones of the supercontinents is subject to exactly the same mechanism as the mid-ocean ridges, with one important difference in the effect. Because their position is fixed, the added solidified mass in the rifts is pressed upwards and downwards and intruded, thickening the adjacent Sial. The volume supplied to the crust of the ridges of one continent dV is equal to the vertical area of one of the rifts (with a length of $6{\cdot}10^3$ [km] and with a crustal thickness h [km]) times the total average polar sea-floor spreading rate, which is estimated to approximately 20 km/My, based on present days sea floor spreading rates, which yields:

$$dV = 1.2 \cdot 10^5 \cdot h \tag{5-4}$$

Notice that this calculation is independent on the number of rifts because we have used the total average polar sea-floor spreading rate, i.e. valid for both polar super continents. As the volume of a supercontinent is the surface area A (which amounts to $1.1{\cdot}10^8$ [km^2]) times the thickness h, the increase in volume dV per unit time t is expressed by the increase in the thickness per unit time, i.e.:

$$dV = 1.1 \cdot 10^8 \cdot \frac{dh}{dt} \tag{5-5}$$

The two equations yield an ordinary differential equation:

$$1.2 \cdot 10^5 \cdot h = 1.1 \cdot 10^8 \cdot \frac{dh}{dt} \tag{5-6}$$

with the solution:

$$\frac{h}{h_{initial}} = 1.1 \cdot \exp\left(\frac{t}{10^3}\right) \tag{5-7}$$

This means that the crust grows exponentially in thickness with time. The initial thickness $h_{initial}$ is the average ocean plate thicknesses, 7 to 8 km (Fowler, 2009). The final thickness at the time of fragmentation (at 160 Ma, see below), i.e. after approximately (4000 – 160) = 3840 Million years is the average continent plate thickness continent which therefore amounts to:

$$h_{continent} = [7 \text{ to } 8 \text{ km}] \cdot 1.1 \cdot \exp\left(\frac{3840}{10^3}\right) = 35 \text{ to } 40 \text{ km} \tag{5-8}$$

According to Fowler (2009) the global average thickness of the continents is 38 km with typical values in the range 30 to 45 km, supporting the calculations outlined here. Hence the thickness of the continental crust can be expressed as:

$$h_{continent} = 0.83 \cdot \exp\left(\frac{t}{10^3}\right) \tag{5-9}$$

In *Figure 5-3* the calculated growth rate function is compared with the observed percentage of total area of continental basement versus time, see Table 10.2 in Fowler (2009). This plot is a further confirmation of the growing mechanism presented here.

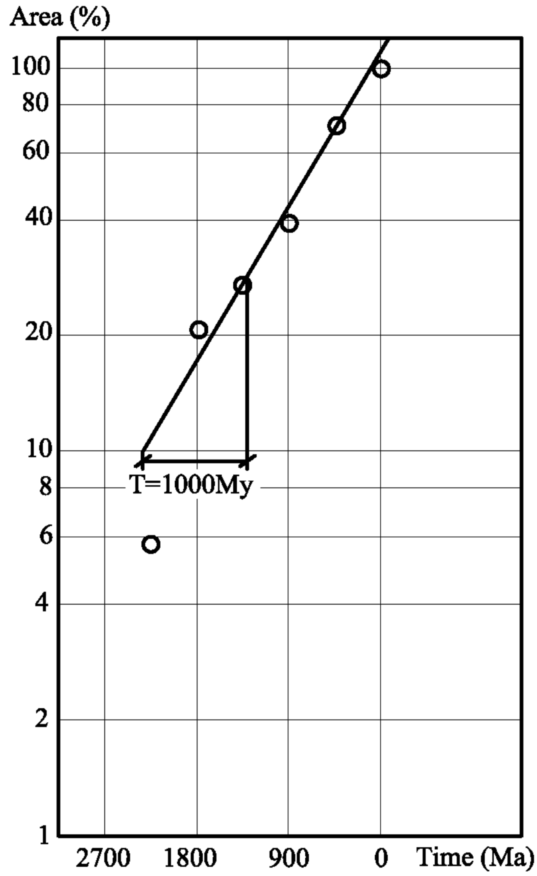


Figure 5-3 The graph shows a Log-Linear plot of the sizes of the measured (open circle) and calculated (line) age-related continental areas [%] versus time of formation [Ma]. The measured values stem from Table 10.2 in Fowler (2009). The time scale in the exponential growth rate is T = 1000 My.

5.5 First appearance of Land at the Supercontinents

Epoch IV. 600 Ma to 160 Ma

As a consequence of the isostatic equilibrium the growing continents are elevated and eventually they break through the sea surface and appear as land. The knowledge of the thickness of the continents versus time enable us to calculate the time where this appearance takes place, provided we have the necessary information on the densities evolved in this process.

According to Turcotte and Schubert (2007) quite good agreement between observations and theory of the Geoide anomaly is obtained by use of the Airy compensation model. In this the density of the crust (2800 kg/m^3) and the mantle (3300 kg/m^3) are assumed to be constant. According to Turcotte and Schubert (2007) the thickness of continental crust with zero elevation with respect to sea level is 30 km. According to Fowler (2009) does the thickness of the continents typically vary plus minus 20%, which implies that the first land appeared at a time when the average thickness was 30/1.2 = 25 km. Inserted in the equation outlined above for the thickness versus time yields the time for this first appearance of land, namely (4000 – 3405) = 595 Ma. Similarly is the time for the average thickness (30 km) appearing as land found to be 414 Ma. These times are interesting in several respects:

- A prerequisite for the first plants, insects and walking fish to invade the solid Earth is of course that the continents come up the ocean. The evolution of plants on land probably started with algae scum in the transition zone between ocean and land. The first evidence of plants on land comes from fossils of plant spores of Mid-Ordovician period, around 475 Ma (Wellman et al., 2003). One of the more important steps in the evolutionary history is the colonization by animals of the continents. The oldest known land-adapted creatures: centipedes and tiny, spider-like arachnids are dating back about 414 Ma, see Monastersky (1990). Dated a little later in the evolutionary biology, around 370 Ma, the transition between fishes and limbed vertebrates occurred; see Ahlberg and Clarck (2006).

- Clues from ancient rocks are helping to produce a coherent picture of how Earth's atmosphere changed from one that was almost devoid of oxygen to one that is 1/5 of oxygen. This is caused by iron being extremely reactive with oxygen which is reflected in the oxidation state of Fe in the rock record. The first indications of increasing oxygen content in the atmosphere are found in rocks a little more than 600 Ma, see *Figure 5-4*. This is in agreement with the time for the first appearance of land, i.e. at the time for creation of continents in contact with the atmosphere. Similarly, the present levels of oxygen were probably not achieved until approximately 400 Ma, again in accordance with the timing calculated above.

- Roughly 550 Ma the first complex animals, such as trilobites, appear in the fossil record. Many scientists have concluded that an increase in the amount of atmospheric oxygen was critical to the relatively sudden evolution of the animals during the relatively short period of time known as the Cambrian explosion, see http://www.fossilmuseum.net/paleobiology/CambrianExplosion.htm.

- What might have led to the apparently rapid accumulation of the stuff in the atmosphere is still an unsolved mystery. One explanation could be that a massive invasion of plants and trees at the newborn land produced oxygen by photosynthesis. Another explanation could be that a major part of the eruptions of volcanoes shifted from sub-sea to the atmosphere some 600 Ma, which dramatically changed the way in which the released oxygen reacted with the surrounding material.

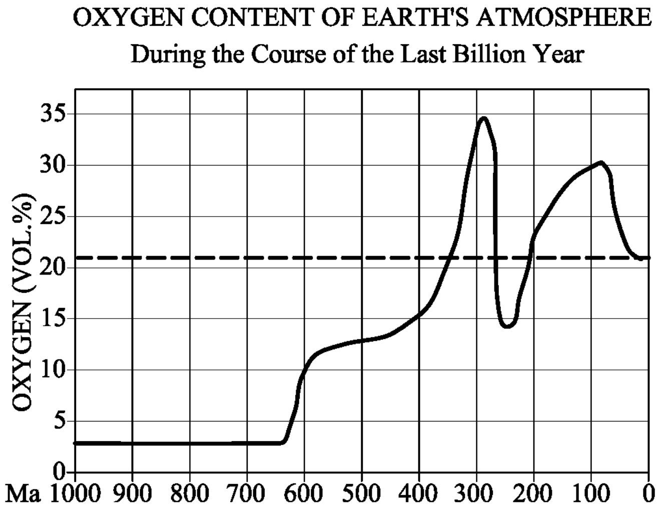


Figure 5-4 Oxygen content of the atmosphere over the last billion year, from www.spacedaily.com/images-lg/oxygen-content-atmosphere-over-last-billion-years. The time of markedly increasing oxygen content in the atmosphere coincide with the time when the first land appears on Earth.

5.6 Fragmentation of the Supercontinents into Present Day's Continents

Epoch V. 160 Ma

In Epoch I it was described how the balance between the centrifugal forces and the gravity forces on the mass of the Earth resulted in the Earth being an oblate ellipsoid. The exponentially growing unbalance in the rotating Earth caused by the export of huge masses from the Equatorial zone (below 35.26° latitude) to the two Polar supercontinents (above 35.26° latitude) eventually results in a resulting Equator-wards gravitational force strong enough to initiate the movement of the fragmented continents towards Equator in order to partly restore the original rotational balance of the Earth. Based on the calculations performed below, it can be stated that this happen at the Southern Hemisphere about 160 Ma, i.e. at a time when the average thickness of the continents have reached about 38 km and the continents had raised about 840 m above sea level. From that date the southern supercontinent was no longer locked in a fixed position and hence the growth of the fragmented continents stopped and a slow but persistent destruction caused by the weather was initiated.

Three of the fragmented subcontinents were heading Equator, namely the South American Plate, the African Plate and the Indian-Australian-New Zealand landmass, while the Antarctic Plate went towards the South Pole to fill the gab left by the continents moved northwards. The continental drift of the fragmented continents has been governed by ridge push caused by long period earth tides combined with slab pull.

In the next chapter we shall reconstruct the continental drift since the fragmentation of the southern supercontinent, including the formation of fracture zones and supplemented by dating of the phenomena.

5.7 Reconstruction of the Continental Drift of the Fragmented Continents

Epoch VI. 160 Ma to present day's

Age-position predictions based on magnetic anomaly dating do yield a safe tracing back of the divergence between two continents. Since the oldest oceanic lithosphere stems from about 200 Ma, magnetic anomaly data can be used only to trace the past movements of the plates back to that time. Nevertheless, if a former convergent boundary with subduction and hence slab pull has disappeared during this reproduction period, then a powerful and important part of the continental movement has been lost together with the ocean crust. This is demonstrated to be the case during the last 160 Ma period.

We use the conceptual model outlined (*Figure 5-1*) as base for reconstructing plate motions since ~160 Ma. No doubt, the South Pole supercontinent was the first to split, which can be seen by the southern subcontinents were the first to take advantage of the new born freedom. We therefore start with the Southern Hemisphere. First we look at some implications for the ocean fracture zones caused by the movements of the fragmented continents. Later we analyse the timing of the movements for the individual continents, to make it probable that they all started at the South Pole at the same time.

Immediately after the formation of the four subcontinents, three of them move northwards, namely:

- South America (**SA**), located in sector S5-S8. When **SA** protrudes the ocean, it over ride the subduction zone S3 and hence a substituting subduction zone must be established. As the fracture line S8 becomes a mid ocean ridge (Mid Atlantic Ridge) the new subduction is established along the western coast of **SA**, explaining the present-day subduction zone along the **SA** Plate (MAP, 1994). The southern tip of **SA** is too weak to withstand the pressure from the expanding ocean plate and the new ocean subduction zone is bended towards east by the east going pressure and the Scotia Plate is formed, probably by the same mechanism as the formations of the peninsulas N3 and N4, i.e. with double sided subduction.

- India and Australia (**IA**), located in sector S6-S7. **IA** behaves like the protruding **SA**, but there are visible differences. Here the fracture line S7 becomes a mid ocean ridge (Central Indian Ridge) and hence the new replacing subduction is established along the eastern side of **IA** (New Zealand and the Fiji Islands have to be included in **IA**, since the new established subduction zone is located outside these Islands). One notice that Australia has only reached about 10° S on its way north and the same has the new formed east-west going ocean fracture zone connecting the old and the new north-south going subduction zones. A glance on this east-west going fracture zone (Map, 1994) shows a conglomerate of double sided converging subductions and of divergent plate boundaries and transform plate boundaries. Present days fast north going Australian plate movement shows that the Australian plate has a subducting slab ahead, i.e. that the southern subduction is the dynamically active of the double sided subduction. The time used to create this new east-west going subduction zone for the Australia Continent has markedly delayed the north going movement of the Australian part of **IA**, while the Indian part of the plate could continue its fast movement (with a slab pull ahead), bringing India in advance of Australia. At present time the roles are adverse, because now the Australian part advances fast with a slab pull ahead, while the Indian part is markedly detained due to the collision with Eurasia some 50 Ma. The **IA** has just started to deform the double subducting peninsula N4, located at the south eastern corner of Eurasia.

- Africa (**Af**), located in sector S7-S8, does not over ride any subduction zones, so it just moves fast north (with a slab pull ahead), expanding the width of the adherent ocean plate due to sea-floor spreading. **Af** collide head of with Eurasia 30 Ma, resulting in a radical slow down simply because its advantageous slab pull was then suddenly replaced by a massive resistance.

- The Antarctic Continent (**ANT**) filled up part of the void after the three north-going continents by moving to the South Pole, where it becomes nearly locked. Lack of fracture zones on the **ANT** means that it does not grow further, contrary to the original supercontinent located at the Pole.

At the northern Hemisphere the supercontinent rifting was more moderate, as only the Mid Atlantic Ridge and the now destroyed northern part of the East Pacific Rise were fully developed, forming two sub-continents, North America (**NA**) in sector N5-N8 and the huge Eurasia (**EUR**) in sector N5-N6-N7-N8. The dominating southern continents have effectively hindered the northern continents to move much towards Equator, although the Arctic Ocean has been formed. At the northern hemisphere, the east-west movements are more important to analyse and might in a first order approximation be taken as a rotation about the North Pole.

According to Fowler (2009) one of the main features of the northern Pacific is that the north-south magnetic anomalies represent only the western half of the pattern and, except for the short ridge segments such as Juan de Fuca Ridge, the mid-ocean ridge (East Pacific Rise) that created the oceanic plate no longer exist. This vanished ridge has been subducted under the North American plate pushed westwards due to the ridge push from the Mid Atlantic Ridge (most effective on the smallest continent). With it went most of the Farallon plate, the name given to the plate which once was to the east of the ridge and had the matching half of the symmetrical magnetic anomaly pattern, see *Figure 5-5*. All that remains are the short segments of the ridge and fragments of the Farallon Plate, present-day Juan de Fuca, Rivera, Cocos and Nazca Plates.

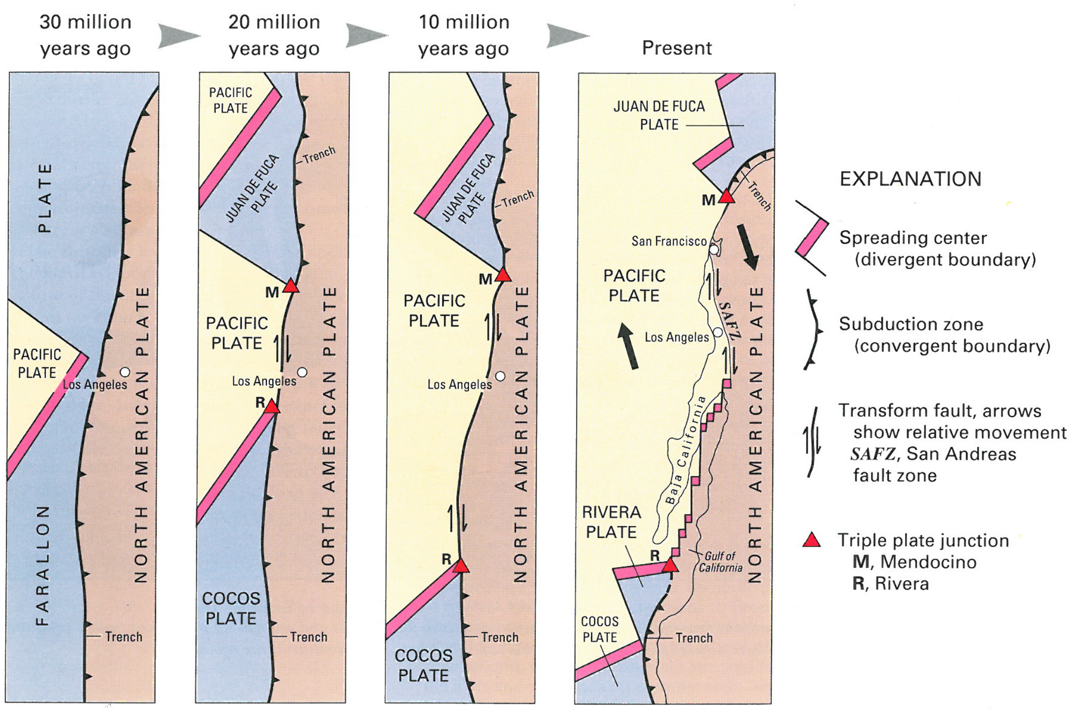
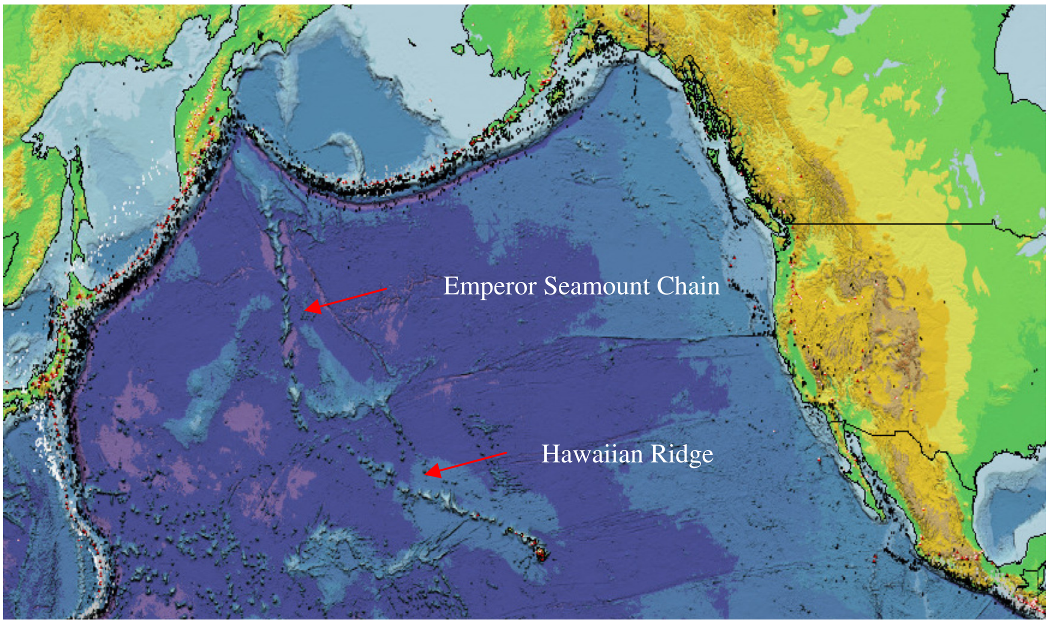


Figure 5-5 Four diagrams illustrating the shrinking of the formerly very large Farallon Plate, as it was progressively consumed by the North American Plate. Adapted from Kious and Tilling (1996).

NA is pushed westwards due to the ridge push from the Mid Atlantic Ridge. This push results in a dismantling of the pulling slab ahead of Farallon plate, causing the formation of the bend in the Hawaiian-Emperor Seamount Chain 40 Ma, see *Figure 5-6*. Before this dismantling event the ocean plate movement was nearly straight north due to the symmetry in the east-west movements in the ancient Pacific Ocean plate. After the eastwards slab pull ceased the plate movement direction changed drastically as illustrated in *Figure 5-6*, creating the well-known bend. This dramatic decrease in the eastwards pressure from the Farallon Plate caused the nearly 35° longitudinal westwards displacement of the Mid-Atlantic Ridge across Equator and of **NA** relative to **SA** and of India (which had become part of **EUR** at that time) relative to Australia, see *Figure 2-1*. One notices that the westwards movement of **NA** causes the weak peninsula N3 to be bended in the opposite direction because **SA** has passed Equator some 80 Ma. Probably this is the cause of the Caribbean Plate (MAP, 1994), i.e. in a way the same conditions that created the Scotia Plate.

The most noticeable at **EUR** is that the continents originating from the southern Hemisphere have nearly closed all the subduction zones at **EUR**'s southern boundary, creating substantial mountain folding and continental rise at **EUR**. One exception is the Peninsula N4, which has only just been touched by the north going southern continents. Besides the continents, the Pacific Ocean (**PaO**) is a marked element on the northern (and southern) Hemisphere, although the expansion of the Atlantic Ocean (**AO**) is at the expense of **PaO**. The reason for the peculiar double subduction zone formation in the western part of **PaO**, see *Figure 2-1*, has probably to be found in some sort of need of an extra mass compensation element although how is not clear at all.

a)



b)

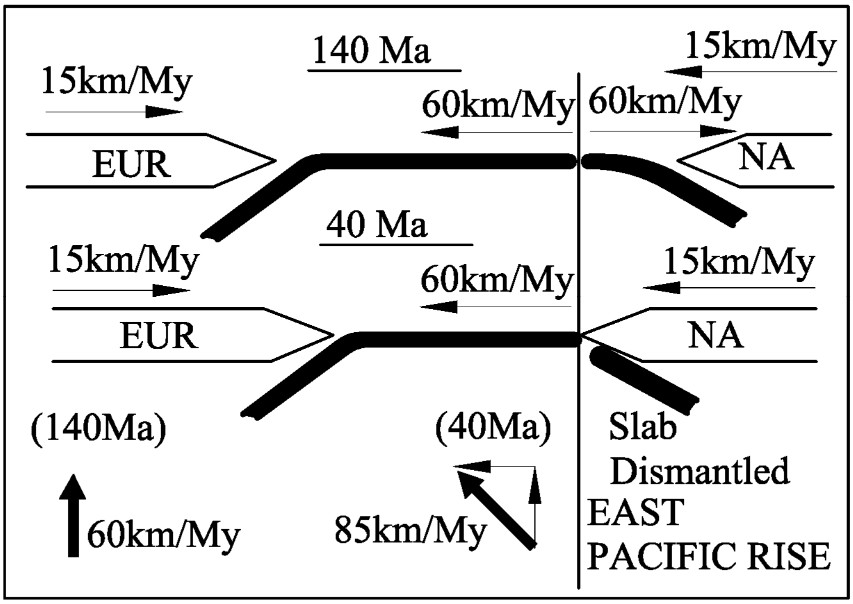


Figure 5-6 ***a)*** *The rows of volcanoes at the Emperor Seamount Chain running nearly north and the Hawaiian Ridge running north-west (Adapted from MAP, 1994).*
b) *Sketch of the event which causes the Hawaiian-Emperor Seamount Chain to bend 40 Ma. Upper sketch shows the movements at the time just before the birth of the North Atlantic Ocean (140 Ma), lower sketch at time 40 Ma when the slab dismantled the Farallon Plate. The two resultant vectors illustrate the plate movement before and after the event at 40 Ma.*

A supplementary confirmation of the scenario outlined above is given by present day's Geoide height anomaly (the height of the Geoide above or below the spheroid) calculated on the basic of satellite observations. In *Figure 4-2a* was shown a slice through the poles of the shape of the Earth averaged over all longitudes (greatly exaggerated). A detailed drawing of the Geoide can be found in Fowler (2009). It clearly demonstrates the ongoing unbalance in the rotational system caused by the two former supercontinents located at the poles, but now partly modified by the north going fragmented southern continents:

- The surplus of mass at the North Pole is visible as an extra height anomaly of nearly 20 m.

- The export of ¾ of the supercontinent from the South Pole shows a present day's deficit corresponding to an anomaly of 26 meter of height.

- At the Equatorial belt the northern deficit caused by the northern continents still located near the North Pole can be seen, and similarly is the surplus mass at the southern Hemisphere in the Equator belt caused by the arrival of the South American Plate, the African Plate and India-Australia Plate to the Equator zone very pronounced.

5.7.1 Timing of the recent ~160 Ma continental drift

Above has been given some sporadic times for certain events. Here we shall try to give a systematic indication of the timing in the continental drift, based on some order of magnitude calculations. We start in the southern Hemisphere.

- South America (**SA**) has reached to ~10° N, i.e. 45° or ~5,000 km. With a slab pull ahead to drive the plate, movement is estimated to 60 km/My, implying a time of movement of say 80 Ma. If the time for start movement for **SA**, **IA** and **Af** shall be the same, it implies that **SA** was radically stopped by a collision with **NA** at Equator some 80 Ma (see the next two calculations).

- India and Australia (**IA**). India collided with **EUR** at ~25° N some 50 Ma. This yields a travelling distance before the collision of 35°+25° =50° of latitude or nearly 6,700 km. With a slab pull ahead the time of movement of this distance is 6,700 (km) / 60 (km/My) = 110 My, and hence the starting time becomes 110+50 = 160 Ma.

- Africa (**Af**) reached ~35° N some 30 Ma. This yields a travelling distance before the collision of 35°+35° =70° of latitude or nearly 7,800 km. With a slab pull ahead the time of movement of this distance is 7,800 (km) / 60 (km/My) = 130 My, and hence the starting time from the southern supercontinent is estimated to 130+30 = 160 Ma.

- The associated separation rate between the Mid-Ocean Ridges and **ANT** is estimated to 20 km/My and should accordingly yield a separation of approximately 30° of latitude in good agreement with present-day position of the ridges.

- Notice that age-position predictions based on magnetic anomaly dating do yield a safe tracing back of the divergence between two continents. Since the oldest oceanic lithosphere is estimated to be formed 160/180 Ma, magnetic anomaly data can only be used to trace the past movements of the plates back to that time. Dating evaluations and estimates given in literature are often flavoured by the false Pangaea understanding, but the timing calculated above is in agreement with the commonly accepted dating for Pangaea to be rifted, namely 170 Ma (Turcotte and Schubert, 2007).

All in all agreement between the estimates indicates that the South Pole supercontinent was split some 160 Ma, i.e. in the Triassic period and therefore started their northward drift at that time.

On the northern Hemisphere a safe estimate based on the method used for the southern Hemisphere is not possible due to lack of large movements with a well known spreading rate. Here, on the other hand do the age-position predictions based on magnetic anomaly dating yield a safe tracing back of the divergence between the two continents. Based on this method the spreading of **NA** and **EUR** started 120/140 Ma, and further north at latitude of Island the estimated starting time is 55 Ma (Fowler, 2009). First, the findings confirm that the rifting started at the South Pole supercontinent. Second, it demonstrates that the rifting proceeded northwards (probably in steps) to the North Pole supercontinent apparently by a wedge effect initiated by the formation of the South Atlantic Ocean.

6. CONCLUSION

Our planet is shaped by plate tectonic processes. A reconstruction of the history of the continents based on what the current literature on plate tectonics offers of viewpoints of the major driving mechanisms, namely convection in the interior and/or slab pull from the dipping ocean plates and hydrostatic ridge push, fails already in an early stage. The reason is that these mechanisms are not able to split the plates and hence create sea-floor spreading, a prerequisite for the formation of continents, divergent and convergent boundaries and transform faults, all the characteristics of our planet.

Therefore, an alternative prime driver of plate tectonics, namely the long period earth tides, was introduced and tested successfully against observations and predictions. The final demand of the new theory was, that applying the rules to be obeyed by earth tides, it should be possible in details to tell the history of the continents, which in the present context has been interpreted as a reconstruction of the origin, growth, appearance as land, fragmentation and drift of the continents until present day's locations. Further on it was demanded too that the boundaries of the plates, i.e. the divergent and convergent boundaries and the transform faults as they appear today could be identified and explained by use of the earth tides theory.

Qualitatively as well as quantitatively the earth tides theory has shown itself capable to explain a great catalogue of geological phenomena's associated with plate tectonics on our planet, inclusive phenomena's which have hitherto been unexplainable and/or unresolved.

7. LIST OF SYMBOLS

Symbol	Value and Unit	Description
a	m	Major axis of the Earth
A	km^2	Area
A	-	Annually
b	m	Minor axis of the Earth
D	°	Declination of planet
E	kg	Mass of the Earth
F	-	Fortnightly
g	9.82 m/s^2	Acceleration of gravity
h	-	Love number
h	km	Crustal thickness
l	m	Length (along meridian circumference)
M	-	Moon, monthly
M	kg	Mass of the Moon
Ma	10^6 years	Million years ago
My	10^6 years	Million years
N	-	North
R	km	Radius in orbital motion
r	m	Radius to geoide
S	-	South, Sun, Solar, Semi
S	kg	Mass of the Sun
t	°	Hour angle
t	s; Ma	Time
T	-	Tertial, index for tidal
T	Ma	Time scale
V	m^3	Volume
z	°	Zenith distance
z	km	Vertical distance
ε	-	Ecliptic
η	m	Super elevation
ω	s^{-1}	Angular velocity
θ	°	Latitude
ρ	kg m^{-3}	Density
ψ	°	Argument (phase) for the moon and/or the sun

Abbreviations for tectonic plates:

- **AI**: Australian–Indian;
- **Af**: African;
- **ANT**: Antarctic;
- **EUR**: Eurasian;
- **NA**: North American; and
- **SA**: South American.

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